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INTERIM REPORT
INDUCER DYNAMICS, PARTIAL FLOW
HYDRAULIC TURBINE DRIVE

By

J. A. King

Prepared For

National Aeronautics and Space Administration

Contract NAS3-10280

Rocketdyne
A Division of North American Rockwell Corporation
Canoga Park, California

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February 1968

CONTRACT NAS 3-10280

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FOREWORD

Rocketdyne, a Division of North American Rockwell Corporation, has prepared this report under National Aeronautics and Space Administration, Lewis Research Center, Contract NAS3-10280, G.O. 08983. This report covers the period from July 1967 through January 1968.

ABSTRACT

Two computer programs, an analog and a digital, have been developed that will predict the transient performance of a low-speed inducer driven by a hydraulic turbine. An inducer-turbine unit has been designed and fabrication is in progress. Steady-state maps of the pertinent components of this unit have been constructed from existing test data and by synthetic mapping procedures. These maps have been used in the computer programs to predict the performance of this unit in the system in which it will eventually be tested. Parametric studies have been made to determine the effect of selected changes in this system. The computer program has also been used to investigate several inducer-turbine combinations in simulated rocket engine installations.

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INTRODUCTION

A major objective in turbopump design is to minimize turbopump weight. This can be done best by using high rotative speeds. A second major objective is to operate reliably at low suction pressures; this is very difficult to accomplish with high-speed turbomachinery. However, the objective can be met by using a low-speed inducer upstream of the high-speed pump to generate sufficient head rise to permit the main pump to operate at all times without cavitating. The low-speed inducer can be driven in a variety of ways, one of which is by using part of the high-pressure discharge flow from the main pump to power a hydraulic turbine that drives the inducer. This research program is concerned with the theory, design, construction, and testing of such a partial-flow, hydraulic turbine-driven, low-speed inducer. Of particular interest is the ability of this inducer to perform as required during conditions of rapid pump acceleration, throttling, and shutdown. Can the transient performance of the inducer be predicted accurately? And if so, what are the variables that most affect this transient performance?

OBJECTIVE

The object of this contract is to develop a computer program that will accurately predict the transient performance of a low-speed inducer driven by a partial-flow, hydraulic turbine. The program then will be used to investigate the transient behavior of a variety of inducer-turbine combinations in a particular system and to determine the effect of selected parameter changes in the system on this transient behavior. The validity of the computer program will be verified by designing, constructing, and testing a turbine-driven inducer to determine its steady-state and transient characteristics. The test results then will be compared with the predicted results. If necessary, the mathematical model will be refined to include measured rather than assumed constants.

DESIGN OF A PARTIAL-FLOW, HYDRAULIC TURBINE-DRIVEN INDUCER

HYDRODYNAMIC DESIGN

Nomenclature

D = diameter, inches

D_m = mean diameter, inches

ΔH = head rise, feet

HP = horsepower

N = rotational speed, rpm

N_{ss} = suction specific speed, $N_{ss} = N\sqrt{Q}/(NPSH)^{3/4}$

NPSH = net positive suction head, feet

ΔP = pressure rise, lb/sq in.

Q = volume flow, gal/min

W = weight flow, lb/sec

Design Points for LO_2 and Water

The contract specified that, at the design point, the inducer NPSH should be 8 feet, in water, and that its characteristics were to be compatible with those of the J-2 oxidizer pump, which was to serve as the high-pressure pump. A J-2 fuel pump inducer design modified to a larger scale was to be used for the preinducer design. These basic "ground rules" did not fix the size or the speed of the unit. Calculations were made on a variety of sizes, with both NPSH and facility limitations being considered. The calculations indicated that the inlet diameter of the inducer should be about 10 inches. Accordingly, a standard-size pipe was selected; the pipe was schedule 40 stainless with an OD of 10.750 inches and an ID of 10.020 inches.

The optimum flow coefficient of the J-2 fuel pump inducer is 0.07, and the inlet diameter of the pipe is 8.015 inches. It was desired to have the same value of Q/ND^3 for the modified inducer. For the J-2:

$$\varphi = 0.2292\ Q/N$$

$$\frac{Q}{ND^3} = \frac{\varphi}{0.2292D^3} = \frac{0.07}{(0.2292)(8.015)^3} = \frac{1}{1685.88192}$$

For the preinducer in water:

$D = 10.020$ inches; NPSH = 8 feet; $N_{ss} = 40{,}000$ (44,250 from test data)

$(NPSH)^{3/4} = (8)^{3/4} = 4.75682847$

$N\sqrt{Q} = (40{,}000)(4.75682847) = 190{,}273.1388$

$$\frac{Q}{ND^3} = \frac{Q\sqrt{Q}}{N\sqrt{Q}\ D^3} = \frac{Q\sqrt{Q}}{(190{,}273.1388)(10.020)^3} = \frac{1}{1685.88192}$$

$Q\sqrt{Q} = 113{,}541.2036$; $Q = 2344.79$; $N = 3929.40$

The inducer head was obtained from a curve of the test data, so the complete values for the preinducer design point in water are:

$Q = 2345$ gpm	$\Delta H = 171$ feet
$N = 3930$ rpm	$\Delta P = 74.2$ psi
$\varphi = 0.07$	HP = 135
$N_{ss} = 40{,}000$	W = 326 lb/sec
NPSH = 8 feet	

The ratio of the pipe size is $R = 10.020/8.015 = 1.25$. So every dimension of the scaled-up inducer is 1.25 times that of the J-2 fuel pump inducer.

Although the design point of the preinducer provided some indication of the flow through the high-pressure pump (inducer flow plus recirculation flow), it did not fix the head and speed of the pump. These variables were open to arbitrary selection. It was decided that if the final unit successfully passed all its tests, it might, with a few modifications, be made available for an actual rocket engine test. Rocketdyne has made many studies on uprated J-2 engines, and the version on which the preinducer would be of most use is the 265K engine. On this engine, the LO_2 pump speed would increase by an approximate ratio of 265:200. The NPSH, therefore, would increase by the square of this ratio, or 1.756. A preinducer would be desirable if such an engine were ever tested. Calculations showed that a 265K engine would require a throughflow of 3314 gpm and a head of 3258 feet. The preinducer running on such an engine would operate at the following values:

Q	= 3314 gpm	ΔH	= 342 feet
N	= 5554 rpm	ΔH	= 168.2 psi
W	= 523 lb/sec	HP	= 434
NPSH	= 16 feet		

Under these conditions, the high-pressure pump would produce a head of 2916 feet and a flow of 4090 gpm at a speed of 10,560 rpm. At the design point in water, the corresponding head of the high-pressure pump is 1459 feet at a flow of 2893 gpm and a speed of 7471 rpm.

Inducer Guide Vanes

The inducer imparts a large amount of whirl to the fluid so that the guide vanes must turn the fluid through an angle of 59.6 degrees to remove all the rotation. It was decided that the best way to accomplish this was to use a scaled-up model of the stator following the J-2 fuel pump inducer (Fig. 14, page 25). This row of 19 airfoils removes 35.6 degrees of rotation and converts most of the velocity head into static pressure. The remaining 24 degrees of rotation is removed by a second

cascade containing 19 double-circular-arc blades, each with a chord of 4 inches and a maximum thickness of 0.4 inch. Each vane has 5 holes of 1/4-inch diameter for the passage of the return flow to the turbine. The total area of these holes is 4.6633 sq in. and the flow through them is 549 gpm with a resultant velocity of 37.7 ft/sec and a velocity head of 22 feet.

The 19 blade stator following the J-2 fuel pump inducer was carefully designed to avoid cavitation; test results have shown that the inducer cavitates first.

Hydraulic Turbine Design

Preliminary calculations were made on several types of turbines. These included a partial admission turbine driving a shrouded inducer through the shroud and a full-admission turbine driving the inducer through a shaft. A three-stage, full-admission turbine was the most promising. In 1966, under Contract Nonr 4507(00) for the Office of Naval Research, Dr. O. E. Balje' issued a Rocketdyne report (R-6805) that presented the results of a study program for the prediction of turbine performance. In the Performance Diagrams section of this report is a figure giving the optimum performance of full-admission axial-flow turbines. This diagram is shown reproduced in Fig. 1. To put the values into the same units as used by Dr. Balje' we have for the LOX conditions

$$D = 5.816/12 = 0.48467 \text{ feet}; \quad Q = 122.30/70.79 = 1.727645 \text{ cfs}$$

$$\sqrt{Q} = 1.31440; \quad N = 5554.31 \text{ rpm}$$

$$Had^{1/4} = (805.17)^{1/4} = (28.37552)^{1/2} = 5.326868$$

$$Had^{3/4} = 151.15265$$

$$D_s = \frac{(0.48467)(5.326868)}{1.3144} = 1.9642$$

$$N_s = \frac{(5554.31)(1.3144)}{151.15265} = 48.30$$

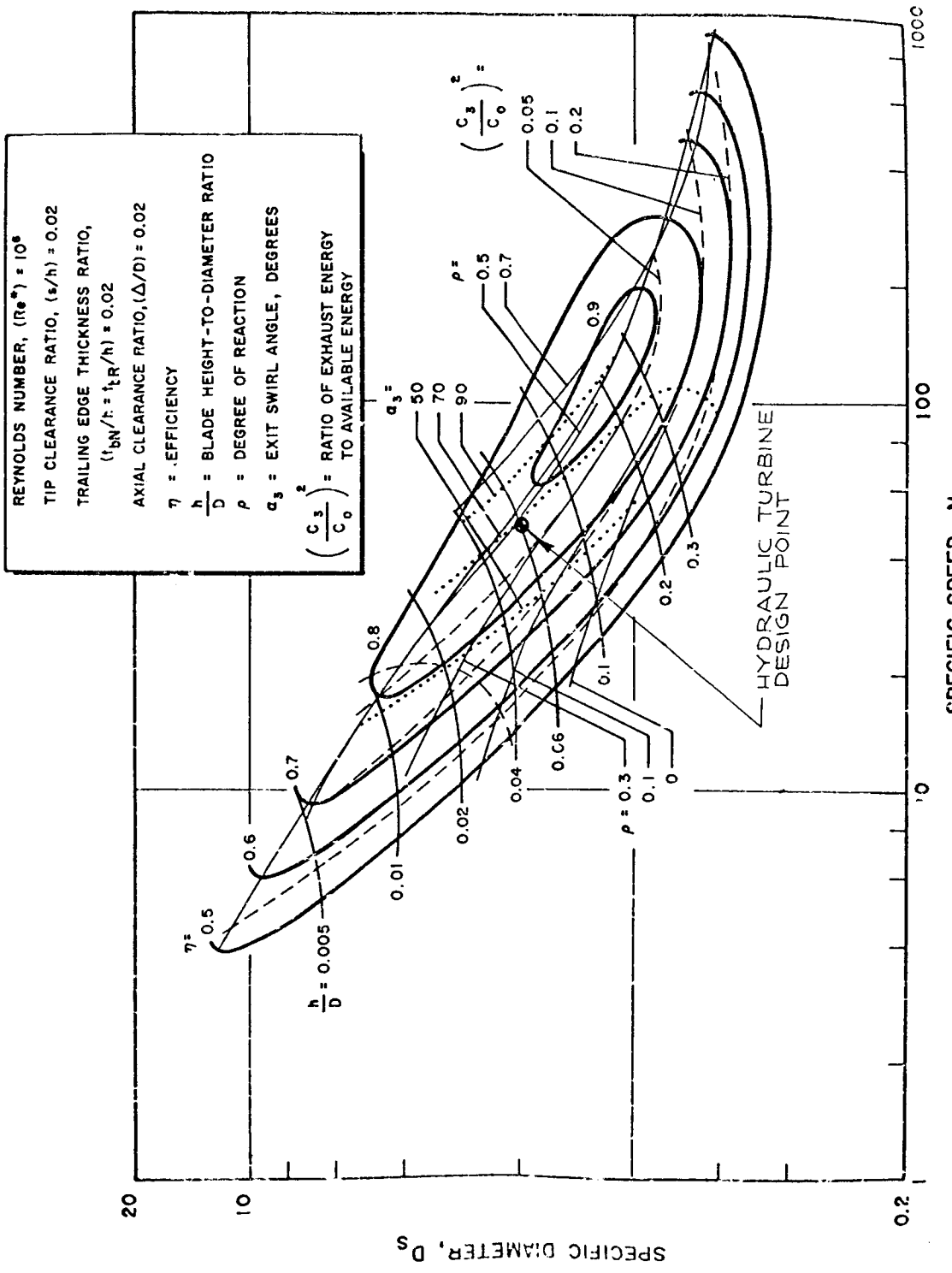


Figure 1. Optimum Efficiency of a Full-Admission Turbine

On this map is shown the operating point of the three-stage hydraulic turbine with a predicted efficiency of over 85 percent. A partial-admission turbine would have an efficiency of approximately half this value and would, thus, require twice the recirculated flow. Additional advantages of the full-admission turbine are:

1. A more easily maintained tip clearance
2. A better dynamically balanced unit
3. A smaller rotating diameter with little or no increase in unit length
4. An unshrouded inducer that is easier to manufacture. Shrouding would change the performance of the J-2 inducer.
5. Seal diameters and speeds that are lower

In view of these advantages, it was decided to use the full-admission turbine.

A generous allowance was made for the head drop in the return line between the high-pressure pump and the turbine. This permitted the insertion of a flowmeter for measuring the return flow and a valve for controlling the speed of the turbine. The remaining head was assumed to drop uniformly across the three stages. This gave a head drop across each stage of 403 feet in water with an Euler head of 325 feet. The resultant Euler efficiency was approximately 80 percent. The resultant turbine flow to provide the inducer design horsepower was 549 gpm. Figure 2 shows the velocity diagram for the three-stage turbine. Figures 3 through 6 show the shapes of the nozzles and rotors as defined by the turbine designer.

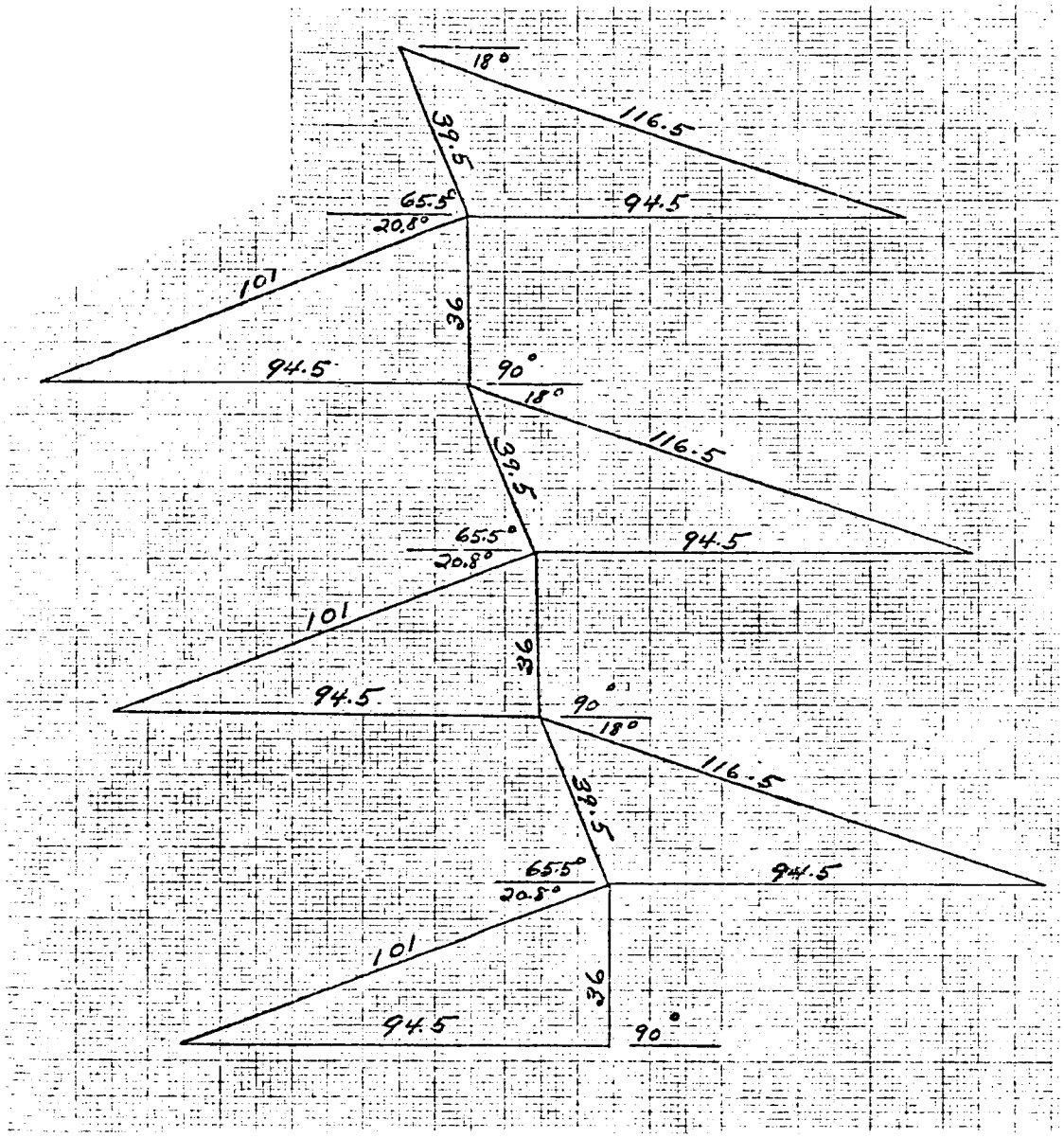


Figure 2. Preinducer Hydraulic Turbine (H_2O) Velocity Diagram

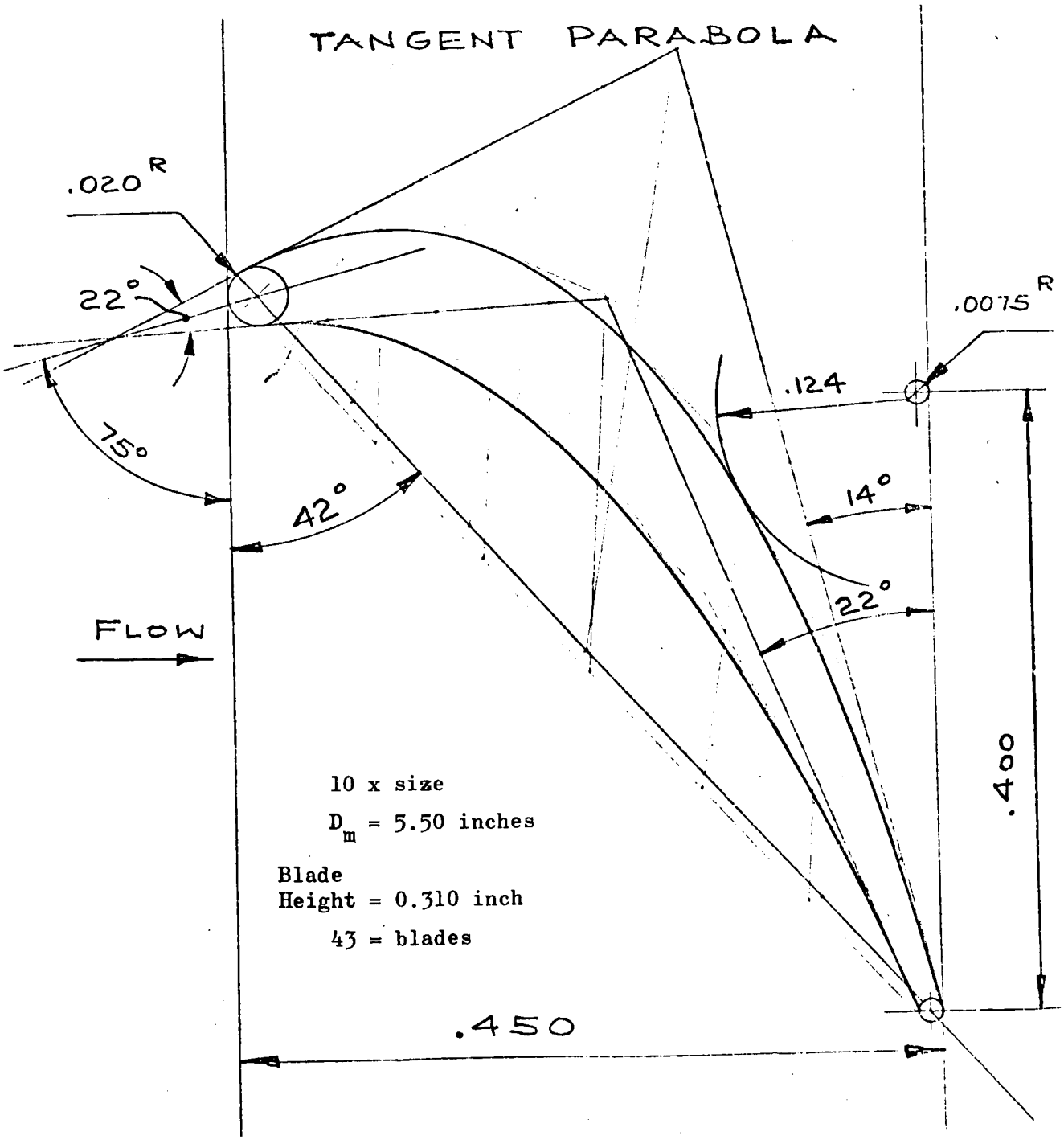


Figure 3. Preinducer Turbine Nozzle

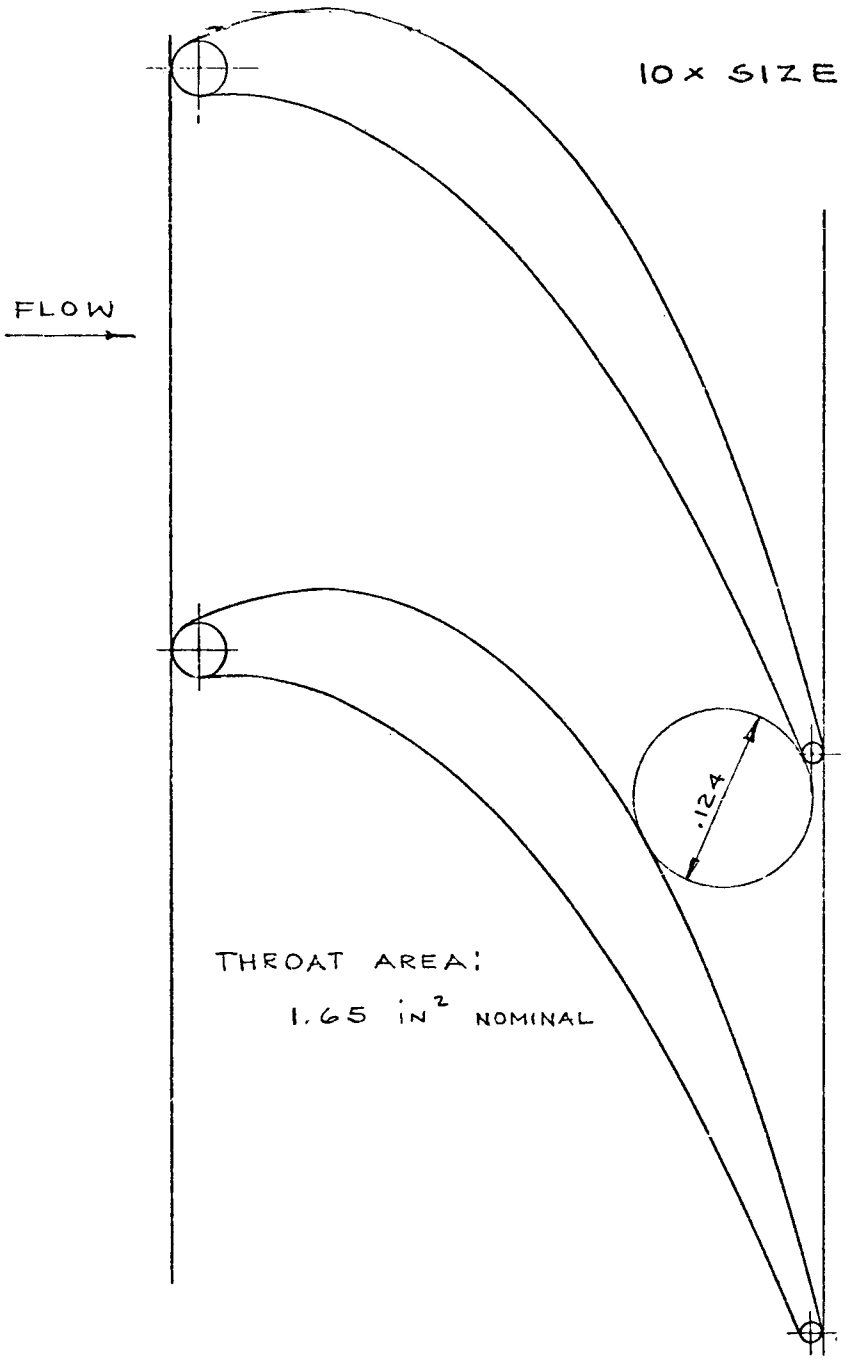
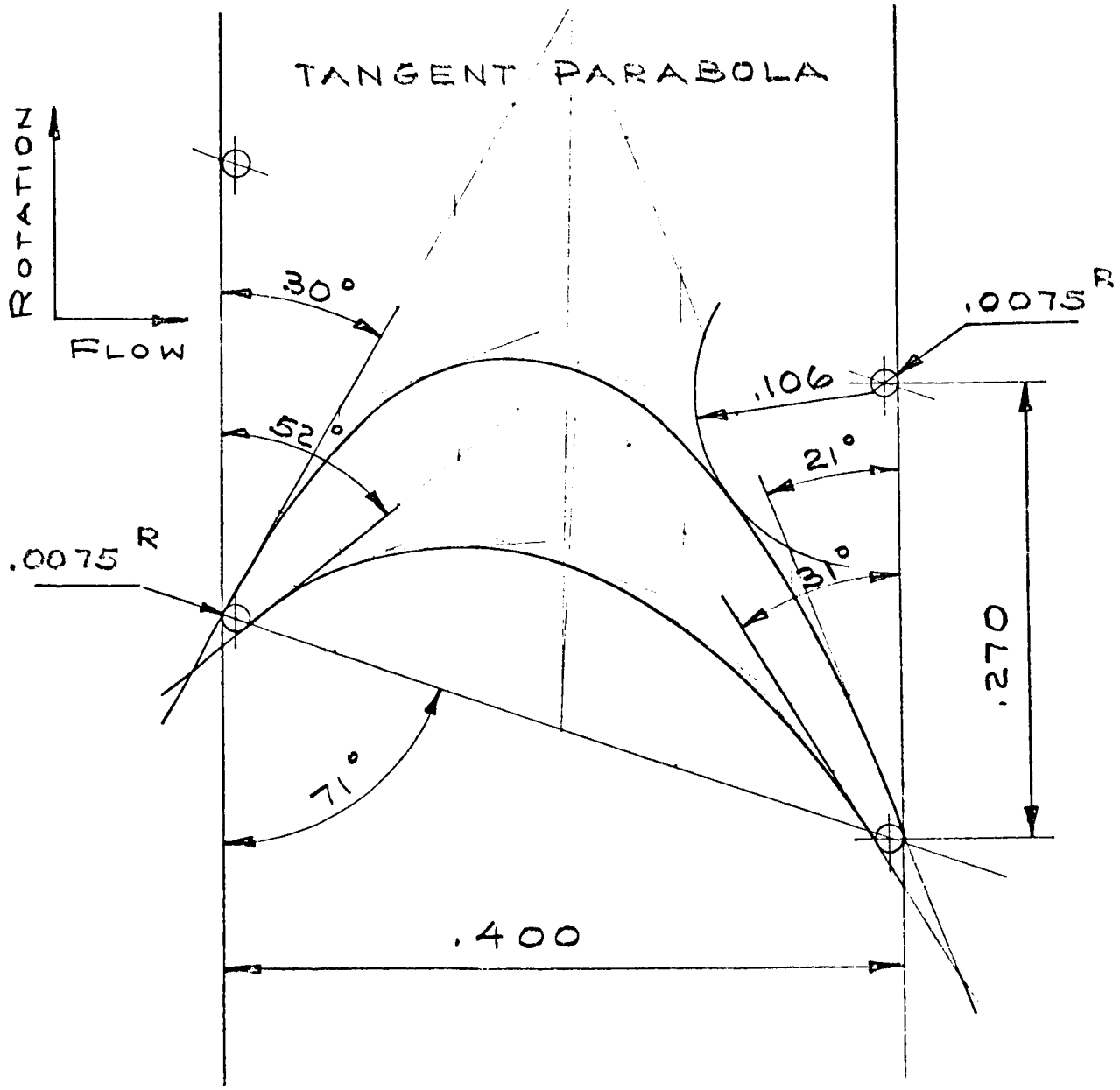


Figure 4. Preinducer Turbine Nozzle



10 x Size

D_m = 5.50 inches

Blade Height = 0.310 inch

64 = blades

Figure 5. Preinducer Turbine Rotor

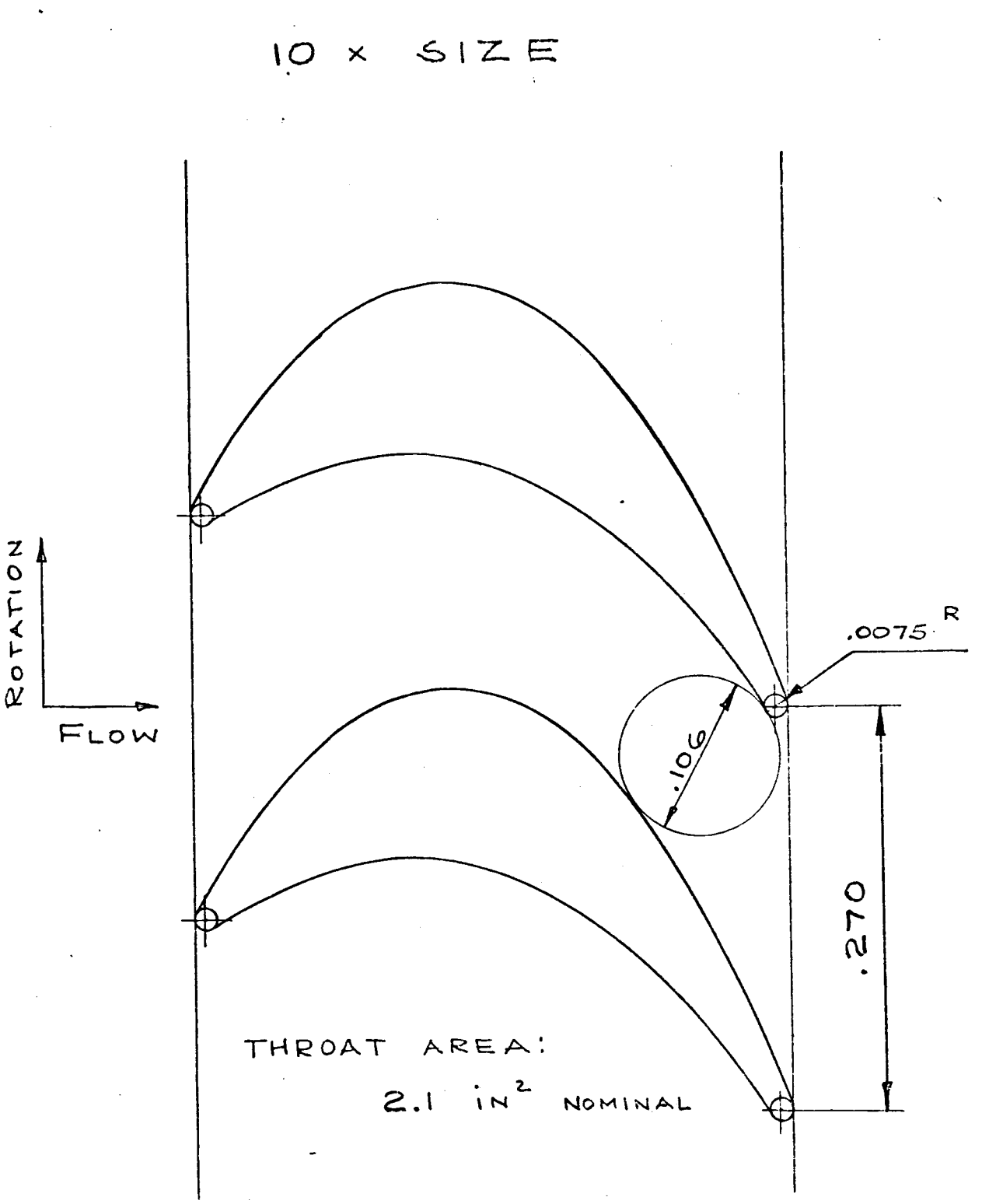


Figure 6. Preinducer Turbine Rotor

Steady-State Maps

The computer programs required steady-state performance maps of the various components as inputs. These include the head, flow, efficiency, and NPSH as a function of speed for both the inducer and the high-pressure pump and the torque, pressure drop and flow as a function of speed for the hydraulic turbine. The high-pressure pump (J-2 oxidizer pump) and the J-2 fuel pump inducer have both been tested at Rocketdyne. Figure 7 shows the nondimensional H-Q performance of the high-pressure pump while Fig. 8 and 9 give the efficiency and NPSH. The nondimensional H-Q and efficiency of the preinducer are shown in Fig. 10, and the cavitation performance is shown in Fig. 11. The H-Q map was taken from calibration tests made on J-2 fuel pumps at full speed in liquid hydrogen. The inlet head was the total head at the inlet of the pump; the discharge head was measured with a static wall tap at the discharge of the stator row that follows the inducer. To this static head was added the head corresponding to the axial component of velocity. It was assumed that the static pressure remained constant through the second row of vanes of the preinducer (the losses were equal to the velocity head recovery associated with the removal of the fluid rotation). The map, thus, includes the effect of incidence on the first row of stators and is accurate at off-design conditions. The maps for the preinducer have been modified by the affinity laws to account for the fact that the inducer is 1.25 times as large as the J-2 fuel pump inducer.

It was necessary to calculate the turbine map because no data were available. The calculated map was based on the following assumptions:

1. The turbine is of the full-admission, repeating-stage type.
2. The flow is two-dimensional and the design is fixed by a velocity diagram at only one radius.
3. The flow is incompressible.

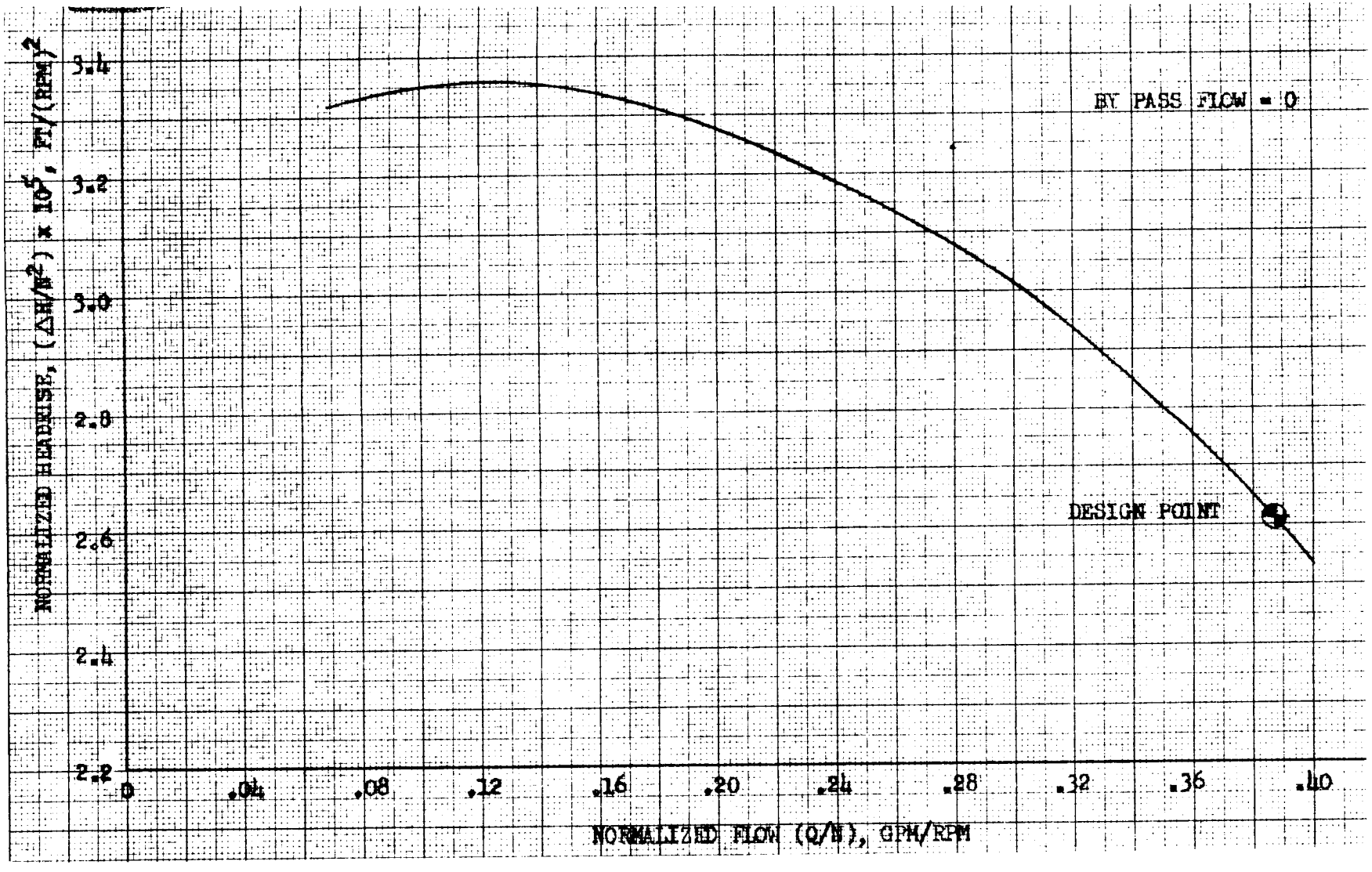


Figure 7. J-2 Oxidizer Pump Performance

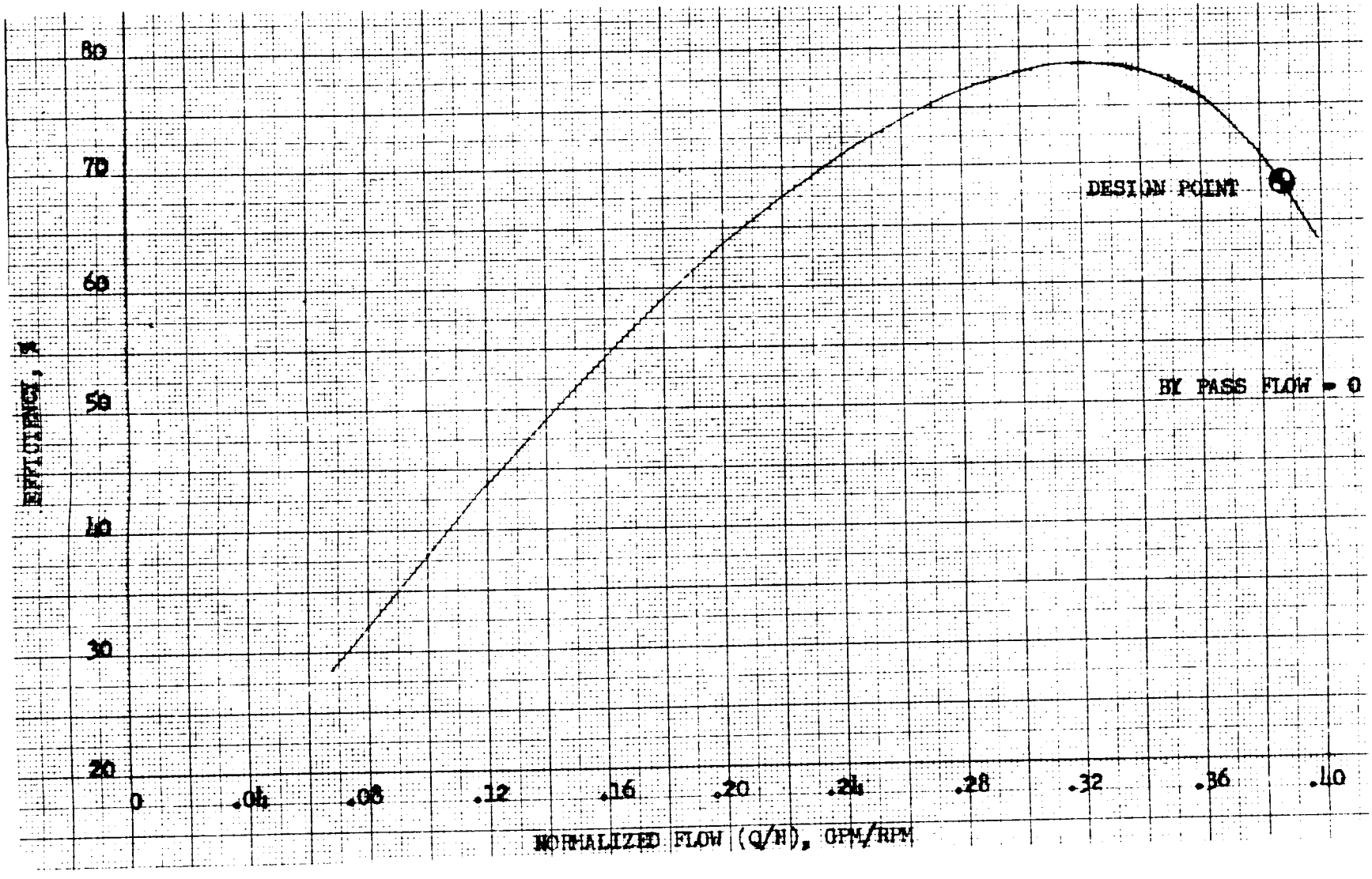


Figure 8. J-2 Oxidizer Pump Performance

Figure 9. J-2 Oxidizer Pump Suction Performance

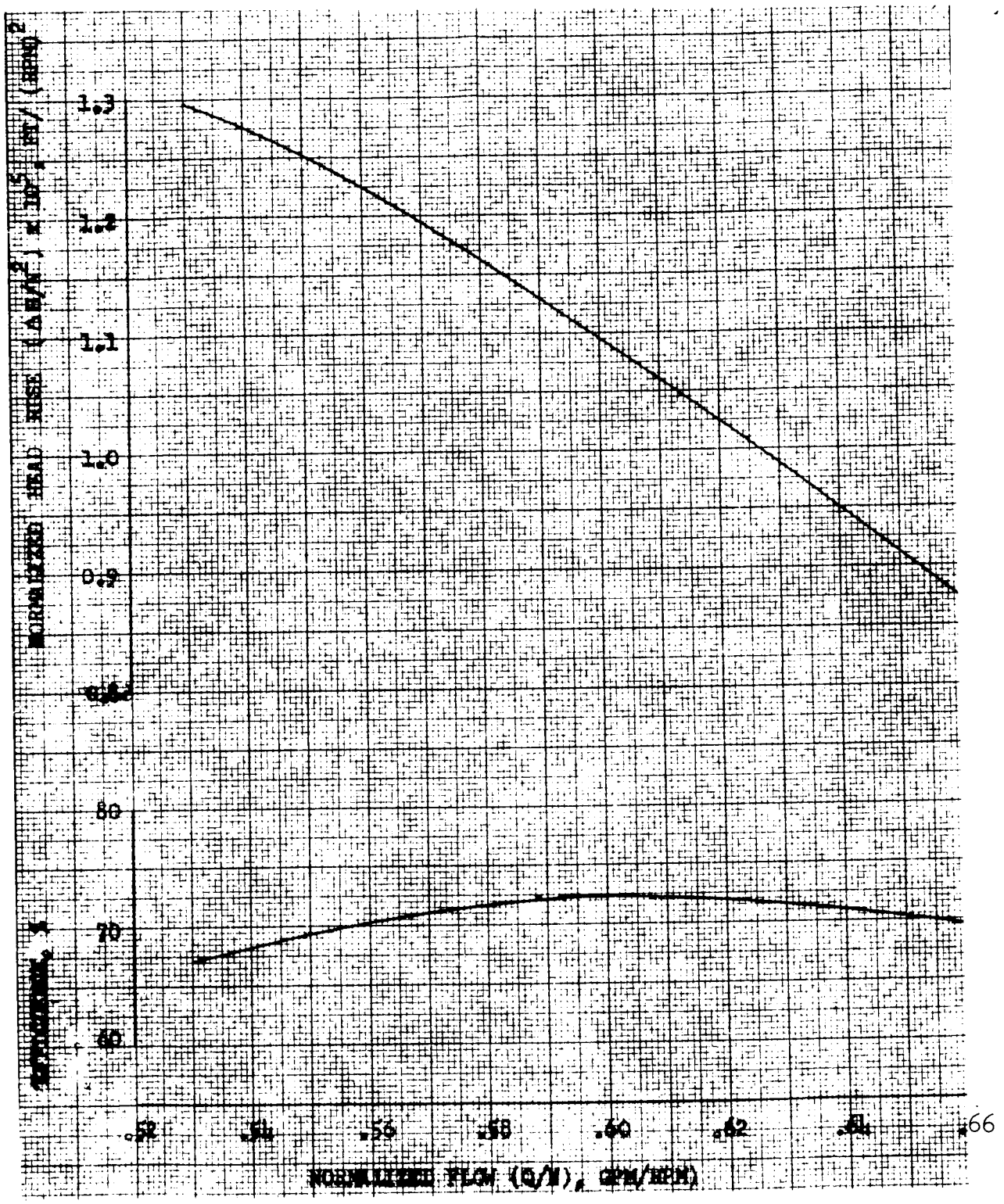


Figure 10. J-2 Oxidizer Preinducer Predicted Performance

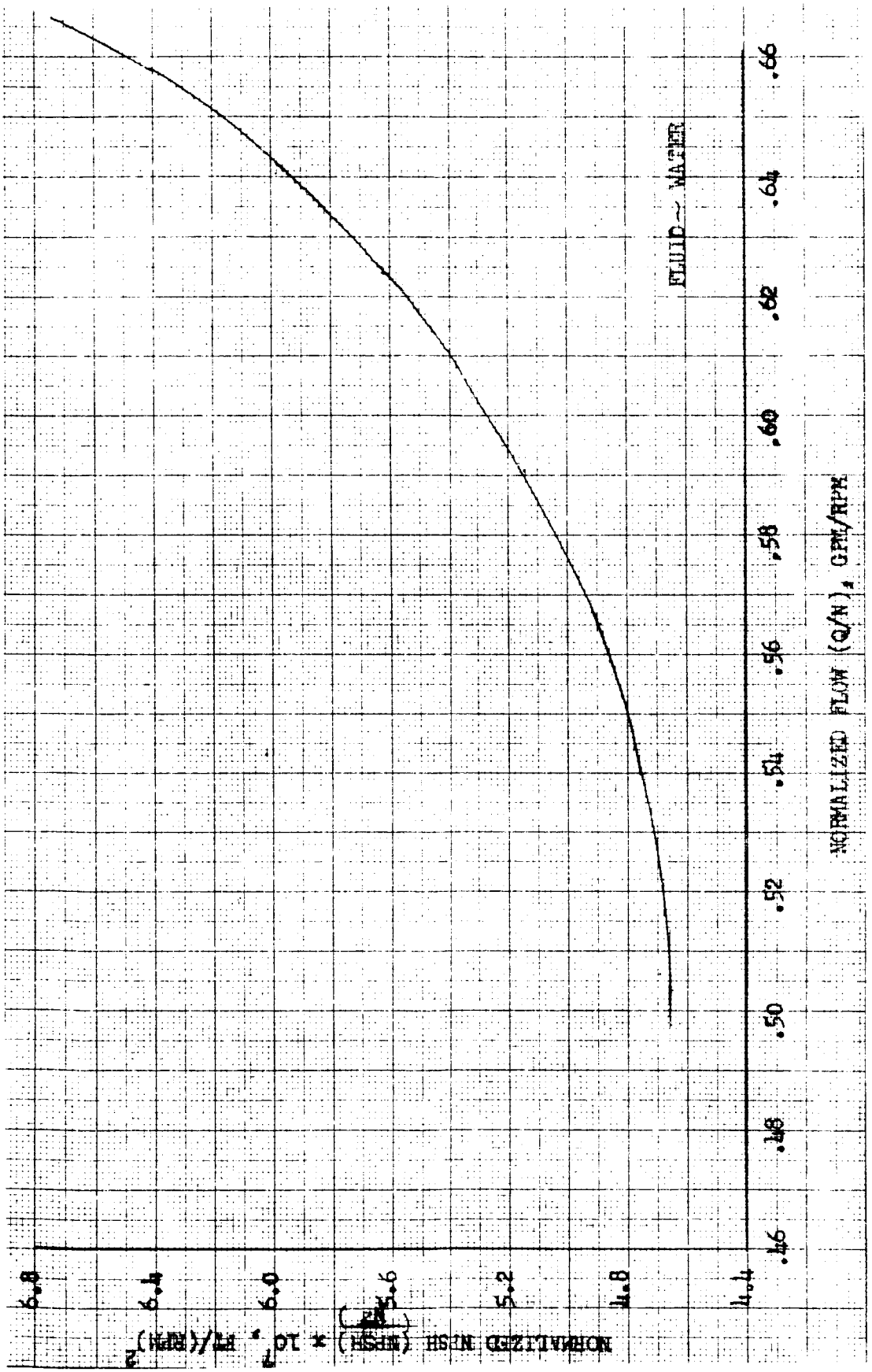


Figure 11. J-2 Oxidizer Preinducer Predicted Suction Performance

4. The nozzle and rotor discharge angles as determined by the basic velocity diagram at the design point are attained by a properly designed set of blades; at off-design points these angles remain unchanged (the deviation angle is not affected by incidence angle).

5. The efficiency at the design point is known (by calculation or estimation). This efficiency is expressed as a loss coefficient applied to the nozzle and rotor spouting velocities; this loss coefficient is held constant at all off-design points. It also is assumed that additional losses are caused by positive or negative incidence angles on both rotor and stator at off-design points. These losses are equal to the velocity head of the component normal to the design inlet velocity vector.

With these assumptions, it was a simple matter to set up the equations and write an IBM program to calculate turbine maps. Figures 12 and 13 show the maps generated by the program. The curve for the three-stage turbine is for the turbine that is being fabricated. The curves for the two- and four-stage turbines were made for parametric studies of the effect of the degree of turbine reaction on the transient performance of the unit. The two-stage turbine was close to being a pure impulse turbine (11.72 percent reaction); the three-stage turbine had 41.14 percent reaction, and the four-stage turbine had 55.86 percent. At first, it was assumed that all turbines had the same axial velocity at the design point. However, this assumption for the two-stage turbine produced too flat an angle leaving the nozzle. This angle (with the tangent) was increased to 14 degrees by increasing the axial velocity.

MECHANICAL DESIGN

A cross section of the preinducer is shown in Fig. 14, with the major hardware components identified. Flow enters the inducer from the left

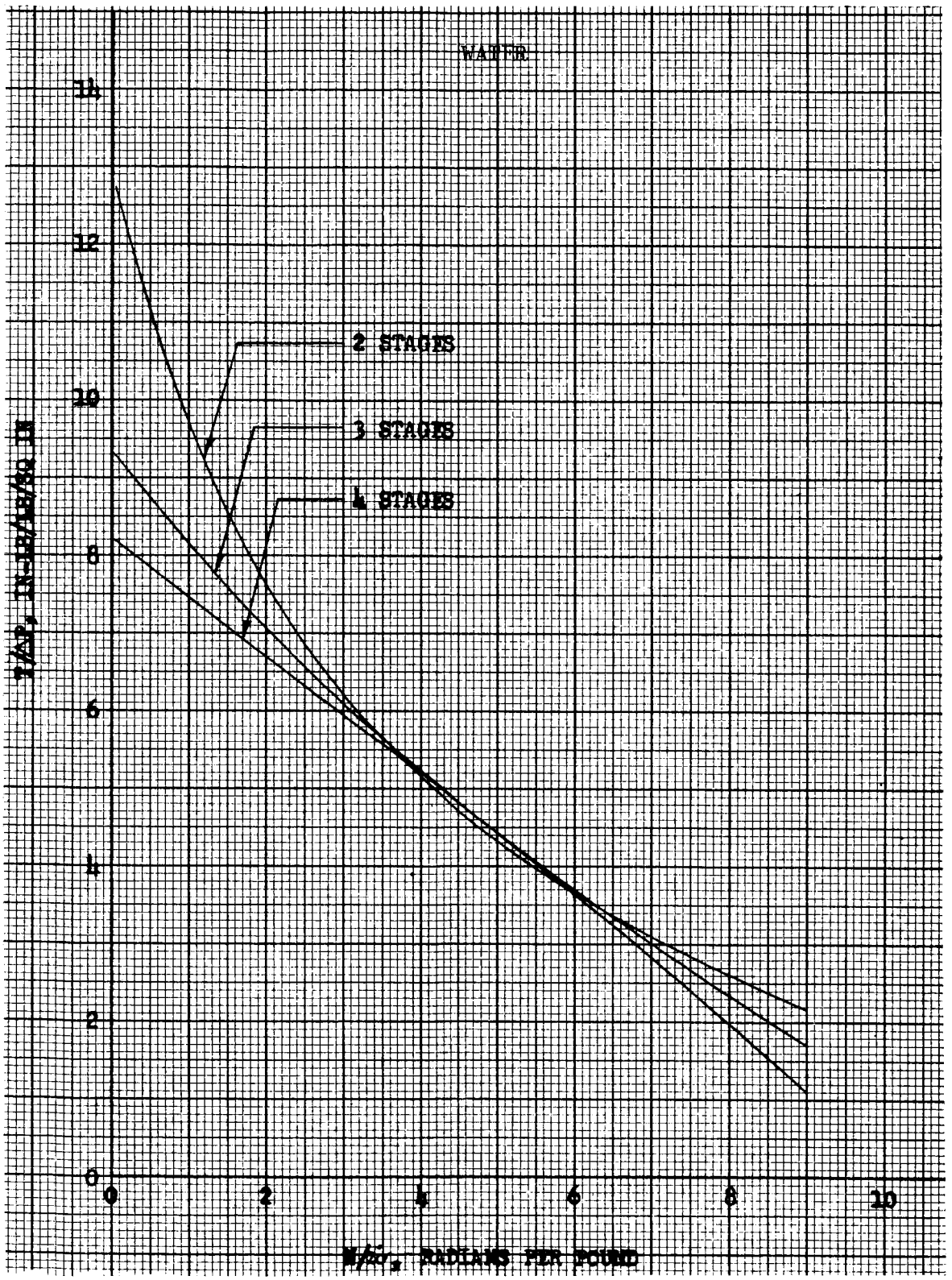


Figure 12. Torque of Preinducer Hydraulic Turbine in Water

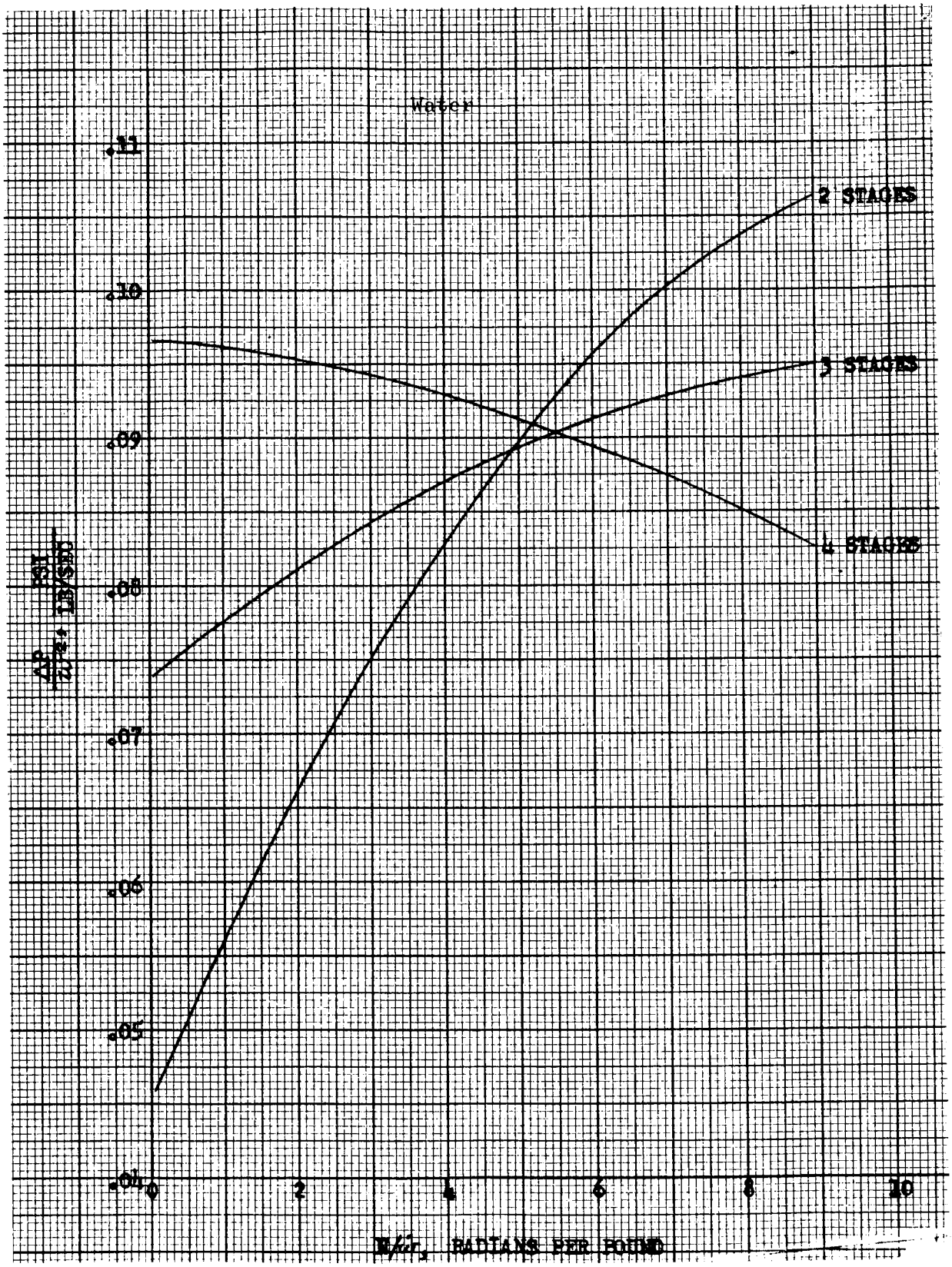
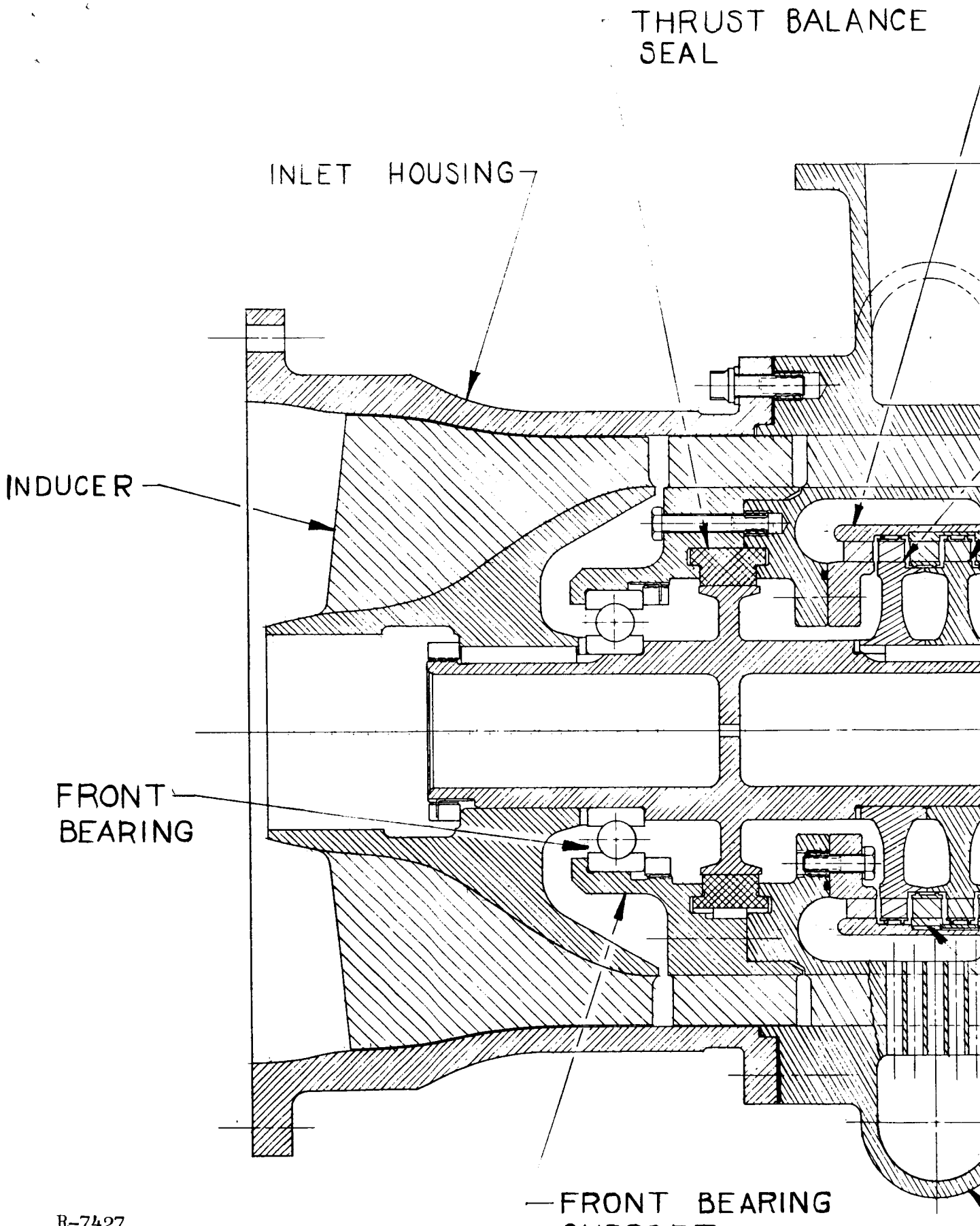


Figure 13. Pressure-Flow Curve of Preinducer Hydraulic Turbine in Water



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FOLDOUT FRAME 1

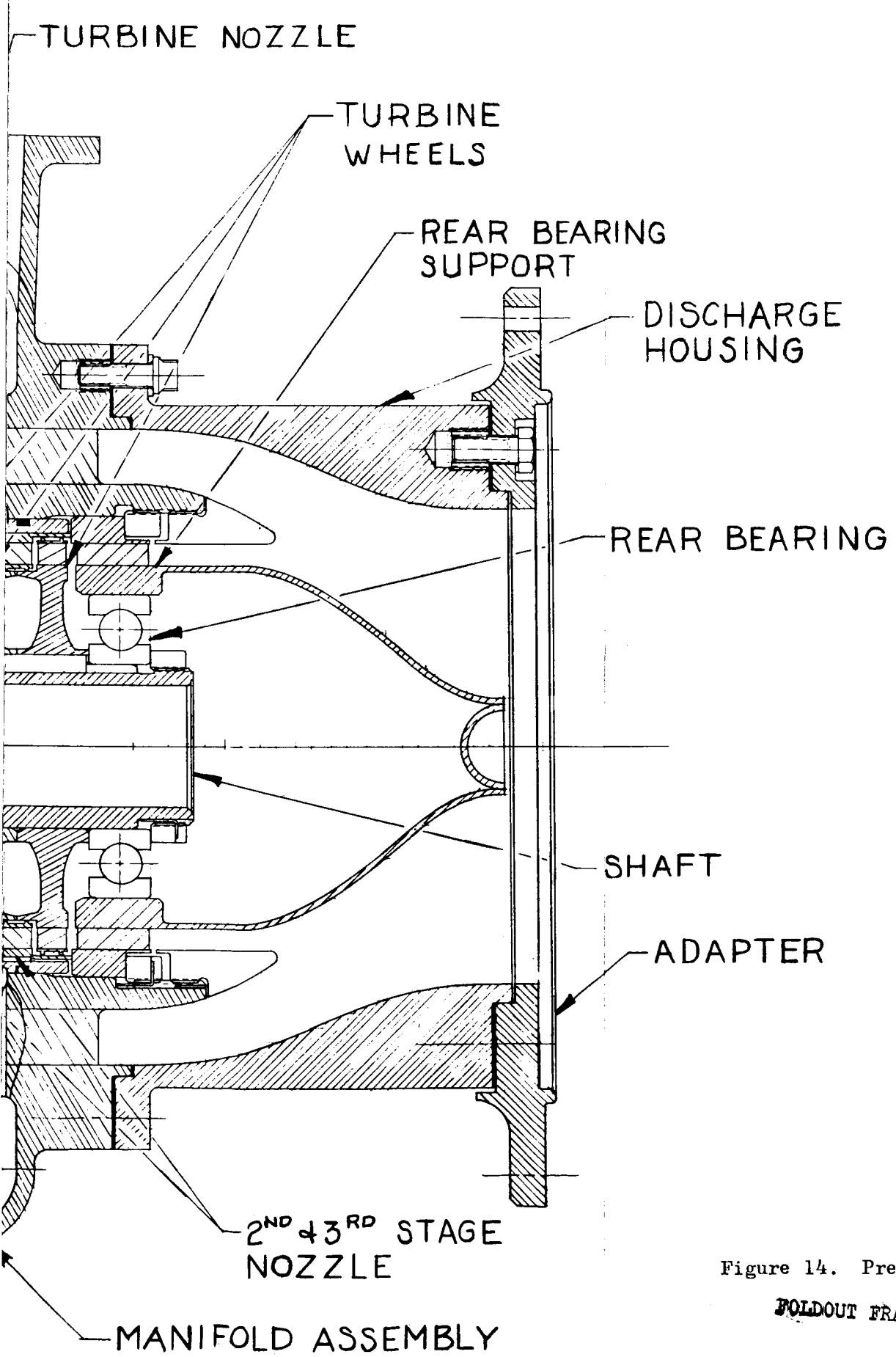


Figure 14. Preinducer Cross Section

FOLDOUT FRAME 2

and is discharged into a two-row cascade. Most of the whirl is removed by the first row of nineteen airfoils; the remaining whirl is removed by the second row. The second-row vanes are used also as structural vanes to support the bearings and the walls of the turbine. The turbine is driven by high-pressure fluid from the discharge of the high-pressure pump. This fluid enters a circumferential manifold through a single inlet and is distributed around the outer periphery from which it passes to the inner circumferential manifold through five radial holes drilled in each of the nineteen vanes. After the fluid has expelled its energy in the turbine, it blends with the inducer discharge flow and enters the high-pressure pump.

The rotor assembly is a flightweight design so that realistic rotor dynamics will be displayed. A critical speed analysis indicates that no critical speed problems will exist throughout the operating range. If a conservative bearing spring rate of 10^5 lb/in. is assumed, the critical speed will be greater than 14,000 rpm. Other numbers pertinent to the rotating assembly are:

Weight	15.67 pounds
Center of Gravity	5.58 inches from inducer end at the hub
Moment of Inertia in Roll	92.83 lb-in.^{2}
Diametral Moment of Inertia	214.95 lb-in.^{2}

The axial thrust of the turbine is in the aft direction; it exceeds the forward thrust of the inducer. The thrust difference is compensated by a thrust balance disk which senses the inducer discharge pressure on the forward side and the turbine nozzle discharge pressure on the aft side. The diameter of the disk is such that a balance is obtained at the design point.

In contrast to the rotor assembly, the housings are heavy to simplify machining and to provide a sturdy support for the rotor.

Inlet Housing

The inlet housing converges the flow from the facility ducting to the inducer inlet OD. It is also the inducer housing and contains the speed pickup. The speed pickup is a Bently transducer located at the inducer blade leading edge OD. The inlet housing wall was left thick to minimize machining costs. As a result of this, the stress level in the housing from both operating and mounting loads is low. The inlet housing is machined from 6061-T651 aluminum alloy hand forging.

Inducer

The inducer is a scaled-up version of the J-2 fuel pump inducer. It is machined from a 7075-T73 aluminum alloy hand forging. A pilot diameter and inducer nut are used for retention to the shaft with a single key to transmit torque. The centrifugal blade loading stresses are quite low; the hydrodynamic blade loading is the largest, being approximately half of the blade design capability. The maximum possible weight has been removed from the inducer hub to keep the rotor assembly flightweight.

Front Bearing Support

The front bearing support incorporates the diffuser vanes as an integral part. It has a retention flange for the thrust balance labyrinth seal. The bearing support is bolted to the manifold assembly, and the bearing is installed in the conventional manner with a bearing shoulder, nut, and lock tab washer. It is machined from a 6061-T651 aluminum alloy hand forging.

Manifold Assembly

The manifold assembly consists of the outer manifold, the second row of diffuser vanes, and the outer shell of the turbine. The vanes, along with the two walls, are machined from solid 6061 aluminum stock, and the

five radial fluid passage holes then are drilled in each vane. The manifold inlet and the manifold ring are separately machined from 6061, then the entire assembly is welded together. This is followed by heat treat and final machining. The maximum stress in this assembly occurs at the elliptical section of the inlet. At the maximum operating pressure, this stress is half the capability of the material. The assembly will be proof pressure tested to 925 psi. The maximum stress at this pressure in the elliptical section will be approximately two-thirds the capability of the material.

Shaft

An aluminum shaft was selected over the conventional steel shaft because the stress levels in the shaft are low. The shaft is hollow and, with the aluminum material, this produces a lightweight low-inertia shaft for fast acceleration response and good rotor dynamics. The shaft is machined from a 6061 aluminum alloy bar. The thrust balance disk is machined as an integral part of the shaft. The finished shaft is heat treated to a T6 condition as per MIL-H-6088. It is hard anodized at the bearing journals and thrust balance seal surface to a thickness of 0.0010 inch. The remaining surface of the shaft is hard anodized to a thickness of 0.0002 to 0.0003 inch. The shaft threads are dry film lubricated to prevent galling.

Turbine Nozzle

The turbine nozzle is machined from 6061-T651 aluminum alloy. There are 43 vanes in the nozzle ring. A cylinder that retains the second- and third-stage nozzle ring is welded to the outer shroud of the turbine nozzle. The turbine nozzle is bolted to the manifold assembly by a flange which is machined on the inner shroud. The split lines between turbine nozzle and the manifold assembly are sealed with O-rings. The highest stress occurs as hoop compression in the welded-on cylinder. This stress is approximately one-half of the material capability.

Second and Third Stage Nozzles

The second- and third-stage nozzles are identical and interchangeable. Their flow passage is the same as that of the turbine nozzle. They are machined from 6061-T651 aluminum alloy; two lips are machined on the inner periphery of the inner shroud to form a seal and reduce fluid leakage between the stationary nozzle and the rotating wheel rim. The nozzle torque is restrained by keying each nozzle stage at the outer shroud to the cyliner of the turbine nozzle. The maximum stress in each nozzle state is in bending at the vane tips where the torque resistance is transferred from each vane into the outer shroud. The stress level in this area is less than one-half of the design capability.

Turbine Wheels

The three turbine wheels are identical except for the spacing rim. The center wheel has the spacing rim on each side, while the first- and third-stage wheels have the rim removed from the front and back side, respectively. The turbine blades are machined without an outer shroud and as an integral part of the disk. The outer shrouds are installed with a dip braze over the blade tips. Two lips are machined on the outer periphery of each shroud to form a seal and reduce fluid leakage over the wheel OD. The turbine wheels are keyed to the shaft. The nozzle-to-wheel axial clearance is set with a spacer between the first-stage wheel hub and the shaft shoulder. The wheels are held on the shaft by the rear bearing nut. The three turbine wheels are machined from 6061-T651 aluminum alloy and heat treated to a T6 condition after the dip brazing process. The highest stress occurs at the blade roots, and this stress is well within the design capability.

Rear Bearing Support

The rear bearing support is machined from 6061 aluminum alloy. The discharge cone is formed from 6061 aluminum sheet and welded to the bearing support. Fifteen vanes are used in the fluid passageway to transmit the bearing loads into the manifold assembly. These vanes are straight and radial and remove any rotation remaining in the fluid. The bearing support is held in place by a single, large-diameter retaining nut.

Discharge Housing

The discharge housing coverges the flow passage from the inducer discharge diameter to the J-2 oxidizer inlet diameter. It is machined from a 6061-T651 aluminum alloy hand forging. The stress level here, as in the inlet housing, is low because the walls were left thick to minimize machining costs.

Bearings

Two ball bearings are used to support the rotor assembly, one aft of the inducer and one aft of the turbine. The two bearings used are the same bearings used in the J-2 oxidizer turbopump. 440-C steel is used for the race and ball material. The bearing cage is made of Armalon with rivited aluminum side bands. Axial retention is maintained on both the inner and outer races of the front bearing. The rear bearing is retained at the inner race only while the outer race is allowed to move axially. The front bearing is lubricated by fluid leakage through the balance disk seal. The rear bearing is lubricated with turbine discharge fluid. This fluid flows to the low pressure inlet through a controlling orifice in the center of the shaft.

Thrust Balance Seal

The thrust balance seal is incorporated into the design to counteract the axial thrust produced by the turbine. The rotating thrust balance disk portion of the seal is machined as an integral part of the shaft. The seal proper is a smooth cylindrical seal machined from Kel-F. The pressure drop across the seal produces a force on the disk opposite that of the turbine thrust.

Adapter

The preindicer discharge housing bolt circle is smaller in diameter than the J-2 oxidizer turbopump inlet flange bolt circle. The preinducer will be installed next to the turbopump, and also in a remote position upstream of the turbopump. Because of these installation locations, the adapter is incorporated to eliminate large bolt circle diameter flanges on the facility ducting and preinducer discharge. The adapter is machined from 6061-T6 aluminum alloy plate. The stresses in this part are low.

DYNAMIC PERFORMANCE MODELS

A mathematical model of the CTL-1 water test facility (including the main pump and drive mechanism, the hydraulic turbine/low-speed preinducer unit, and required feed lines) was formulated for the purpose of (1) studying the transient and low-frequency dynamic behavior of the test system, (2) determining the effect of variations in the preinducer design parameters and test system line configurations, and (3) predicting rocket engine feed system performance incorporating hydraulic turbine-driven preinducers with liquid hydrogen and liquid oxygen propellants.

The system equations and component descriptions were programmed for solution on both an analog and digital computer. The digital model provides the capability for using detailed component performance descriptions (due to larger programming capacity), a means to evaluate any model simplifications required for the analog program, and a concise program deck which can be used at other computing installations. This model was used as a cross check for the analog model and to predict preinducer operation in a simulated rocket engine.

The analog model provides the capability for determining the effect of various system variables in a short period of time. This model was used to conduct system parametric studies, and will be used for model correlation with test data.

EQUATION DEVELOPMENT

The system that was mathematically simulated was the pump test configuration as installed in the CTL-1 water test facility. This system, shown schematically in Fig. 15, consists of a water supply tank with a tube bundle resistance at the outlet, a preinducer inlet feed line, a hydraulically driven preinducer either close or remote coupled to a high-head

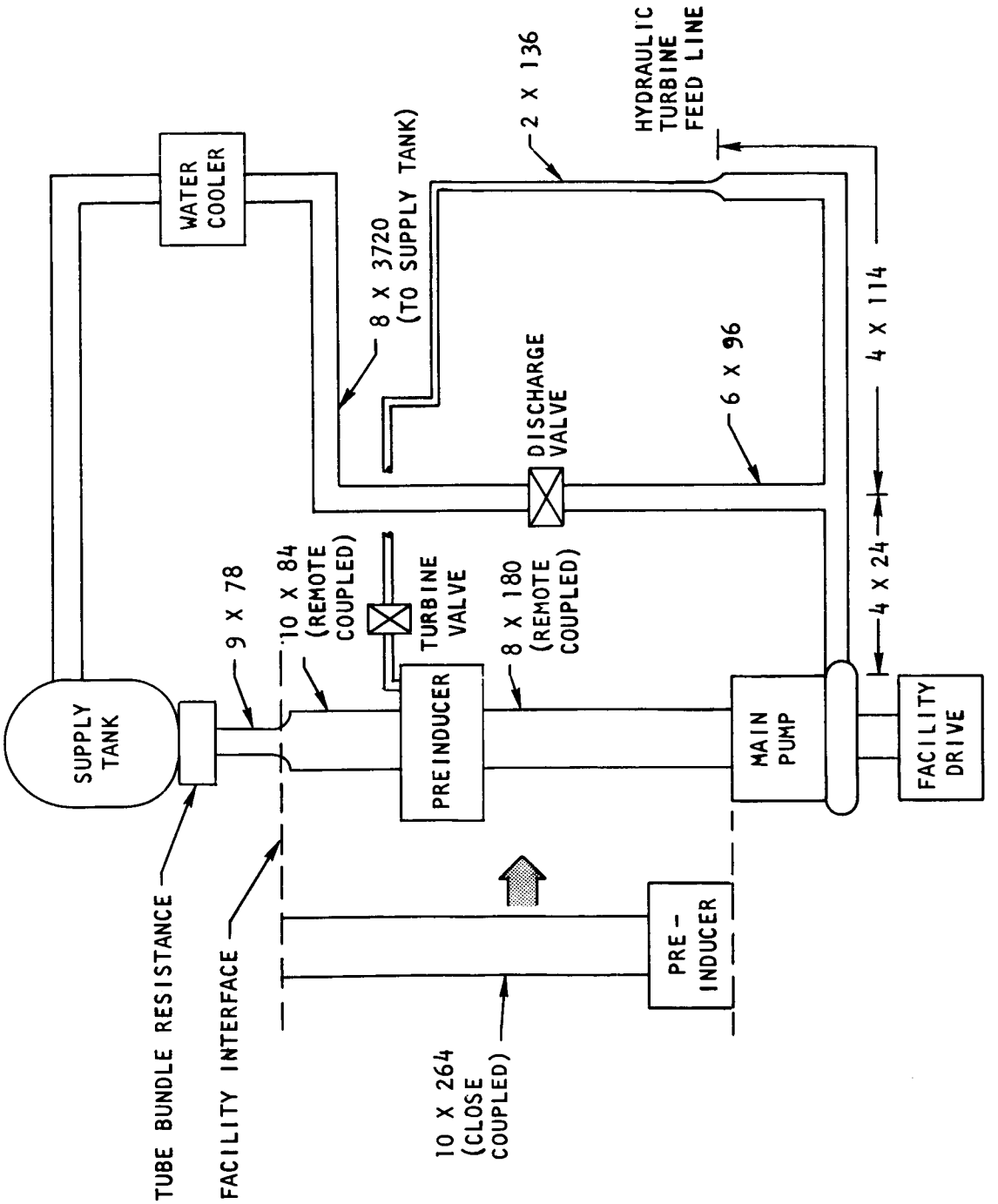


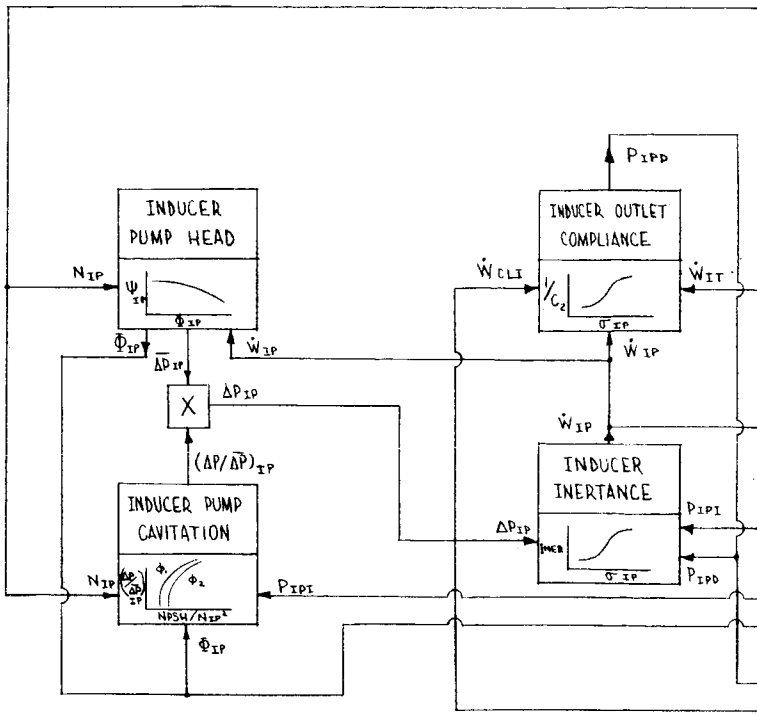
Figure 15. Test System Schematic

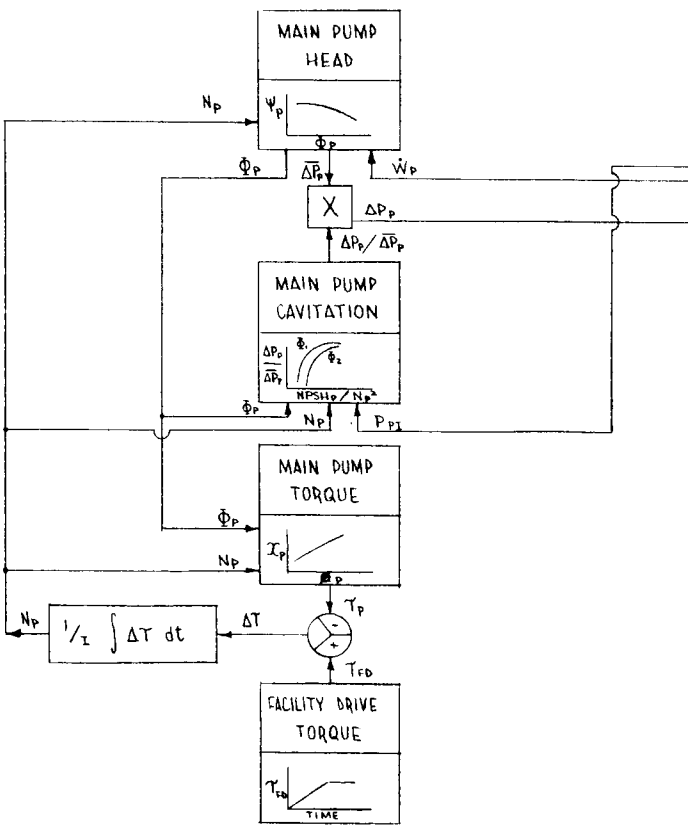
(main) pump, a feed line from the main pump discharge to the hydraulic turbine inlet, a return line from the main pump discharge to the supply tank, and an electric-motor drive for the main pump. With the exception of the main pump drive and tube bundle, the equations required for simulation of the test facility are applicable to an engine feed system with changes in appropriate constants. The electric drive and tube bundle are applicable only to the test facility, the electric drive being used in place of a turbine, and the tube bundle being used to reduce the inducer inlet pressure for low NPSH operation.

The logic flow chart used for developing the models is presented in Fig. 16, which shows the various components, performance curves, and information flow between elements that were considered in building the simulation. The dynamic operation of the pump, turbine, and inducer were represented by performance curves in addition to algebraic and differential equations describing their dynamic behavior. Feed system dynamics were described by distributed or lumped parameter equations, as applicable. The equations used to construct the model are presented in the appendix. Component performance curves are presented in Fig. 17 through 27.

The modeling was based on the following basic criteria and assumptions:

1. The model must be capable of responding to frequencies up to 50 cps.
2. The test fluid (water) density is constant.
3. Pressure drops are proportional to the flowrate squared.
4. Heat transfer can be neglected.
5. Preinducer cavitation dynamics can be represented by a combination of an inlet and outlet compliance separated by an inertance.





FOLDOUT FRAME

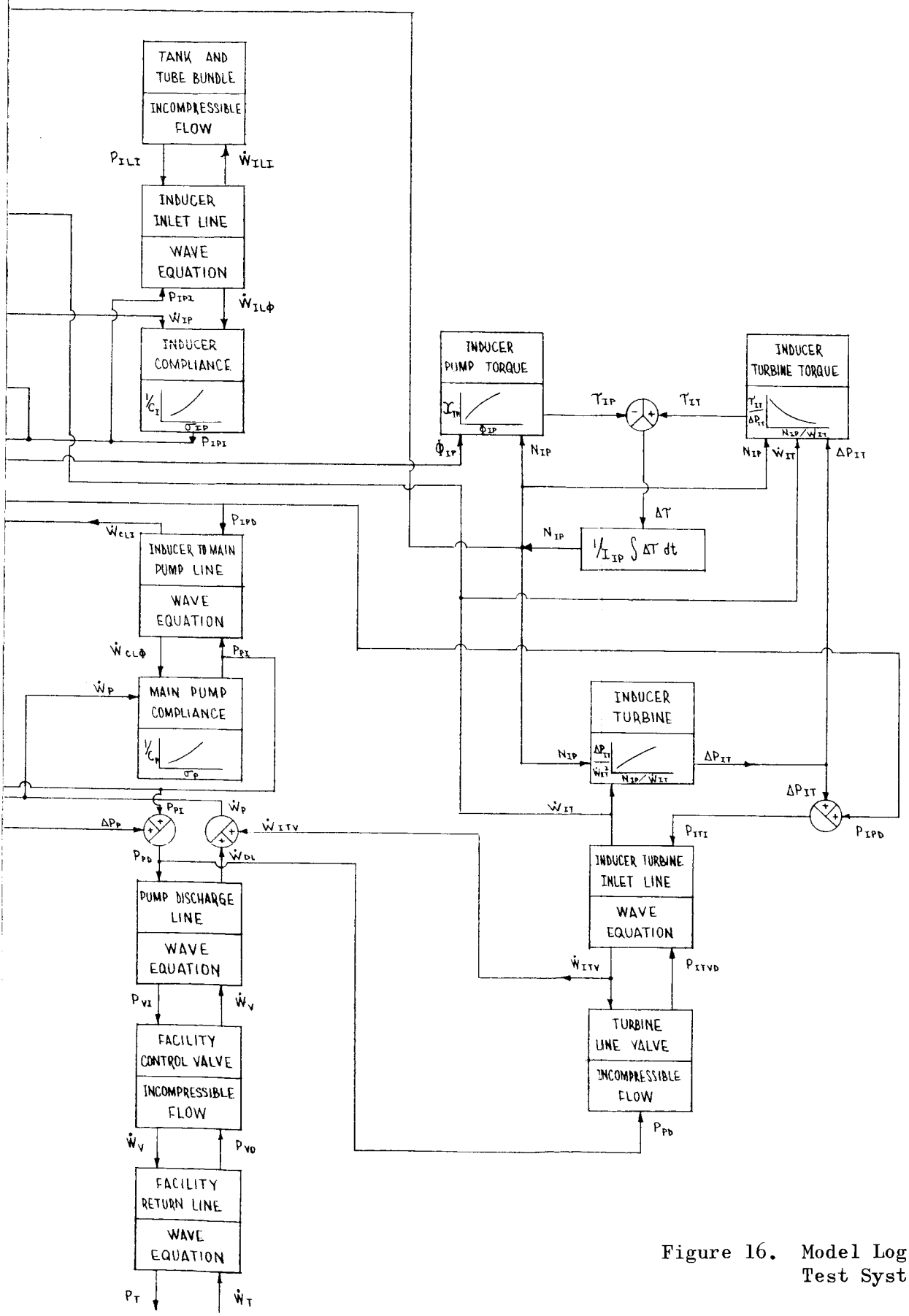


Figure 16. Model Logic for Inducer-Pump Test System

FOLDOUT FRAME 2

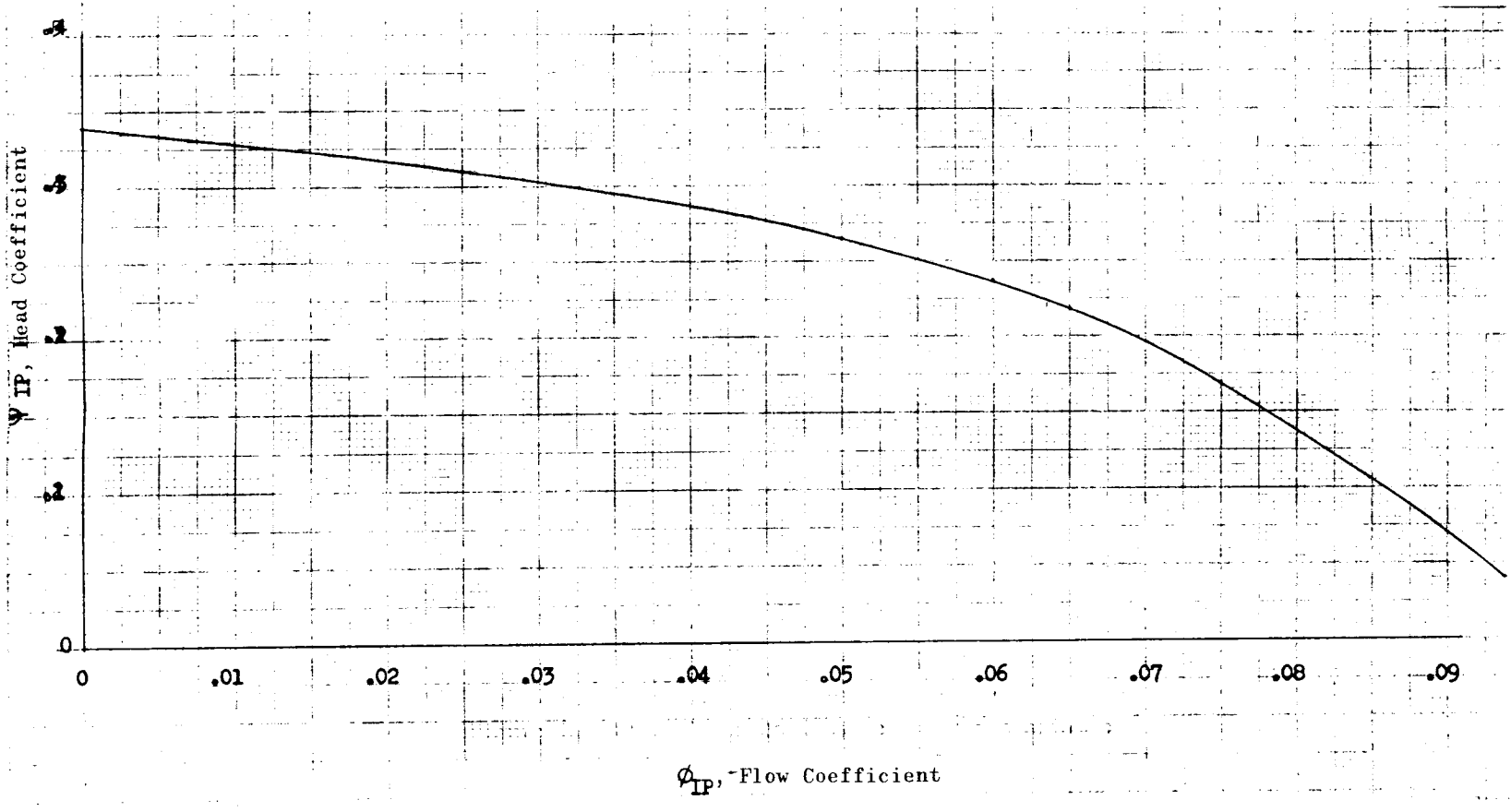


Figure 17. Preinducer Head Capacity Characteristic

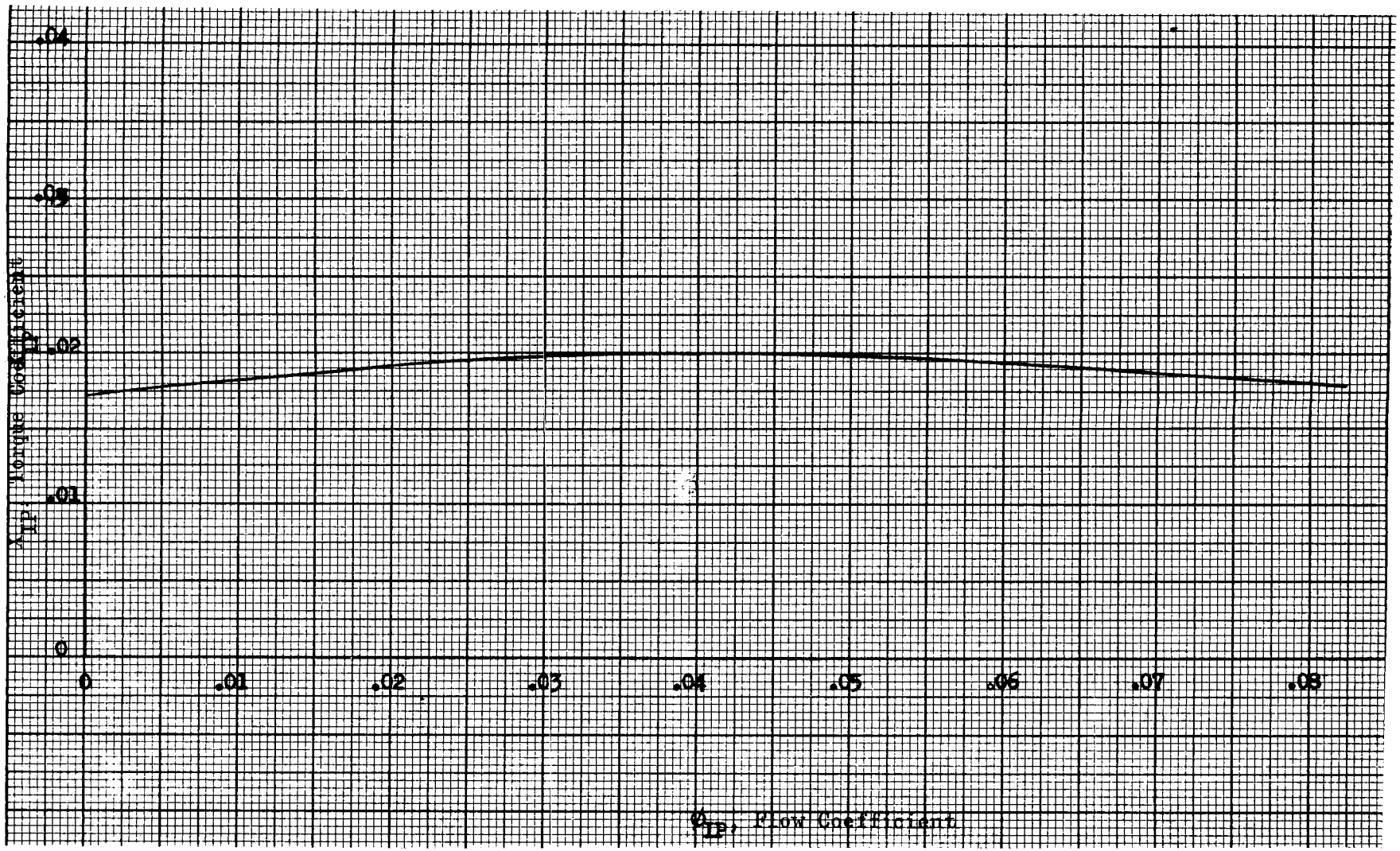


Figure 18. Preinducer Torque Capacity Characteristic

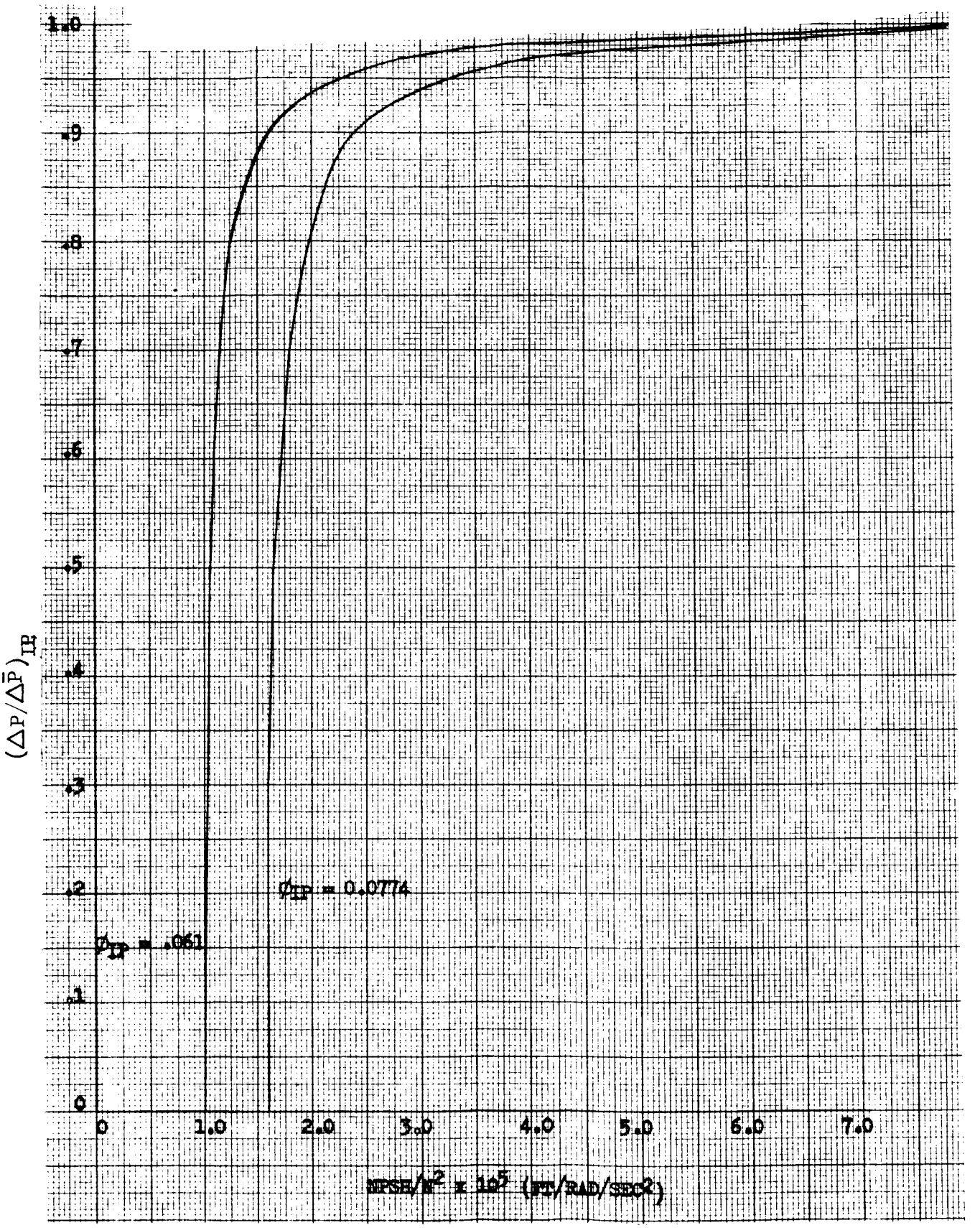


Figure 19. Preinducer Cavitation Correction

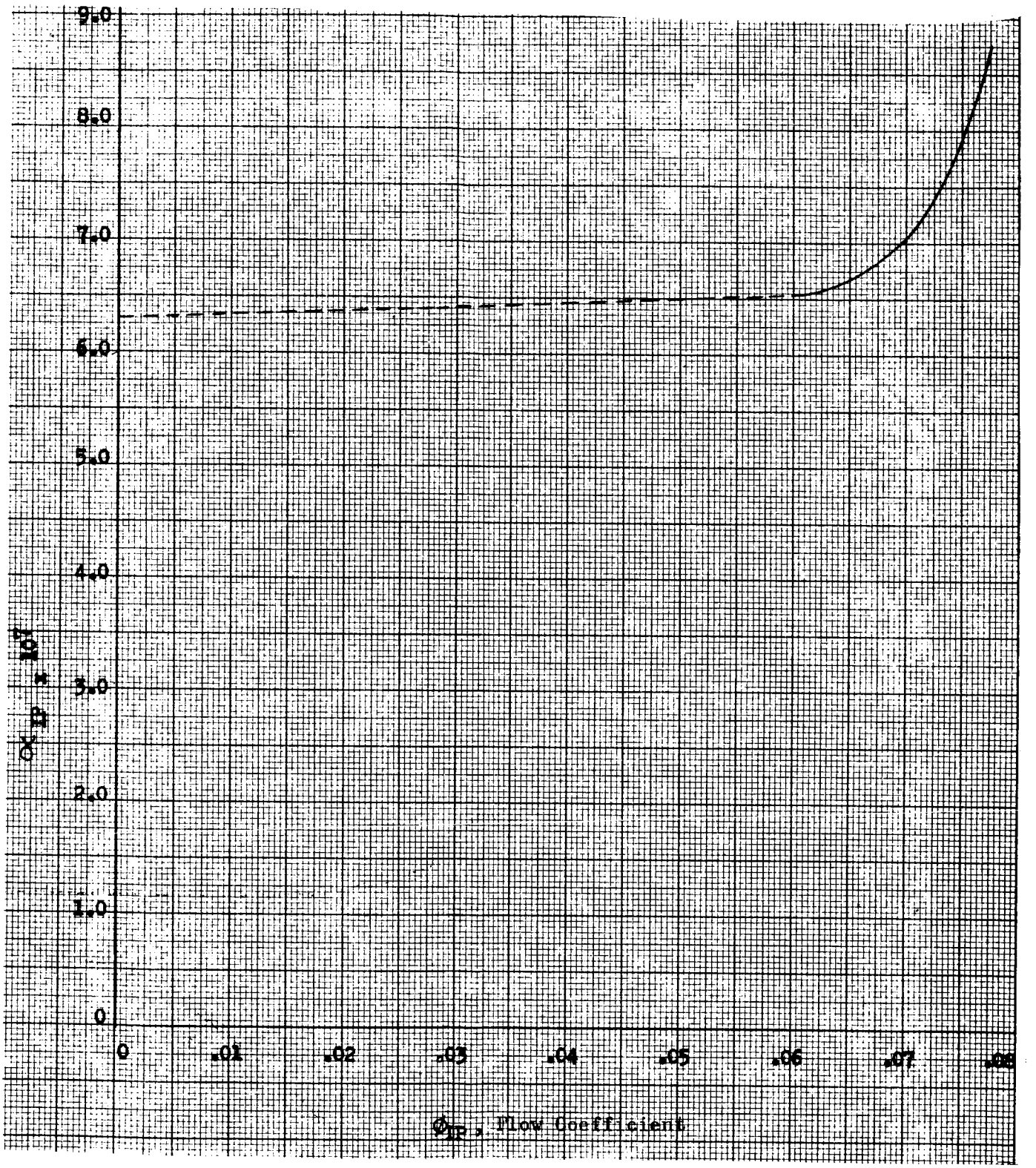


Figure 20. Preinducer (H_2O) Cavitation Correction Parameter

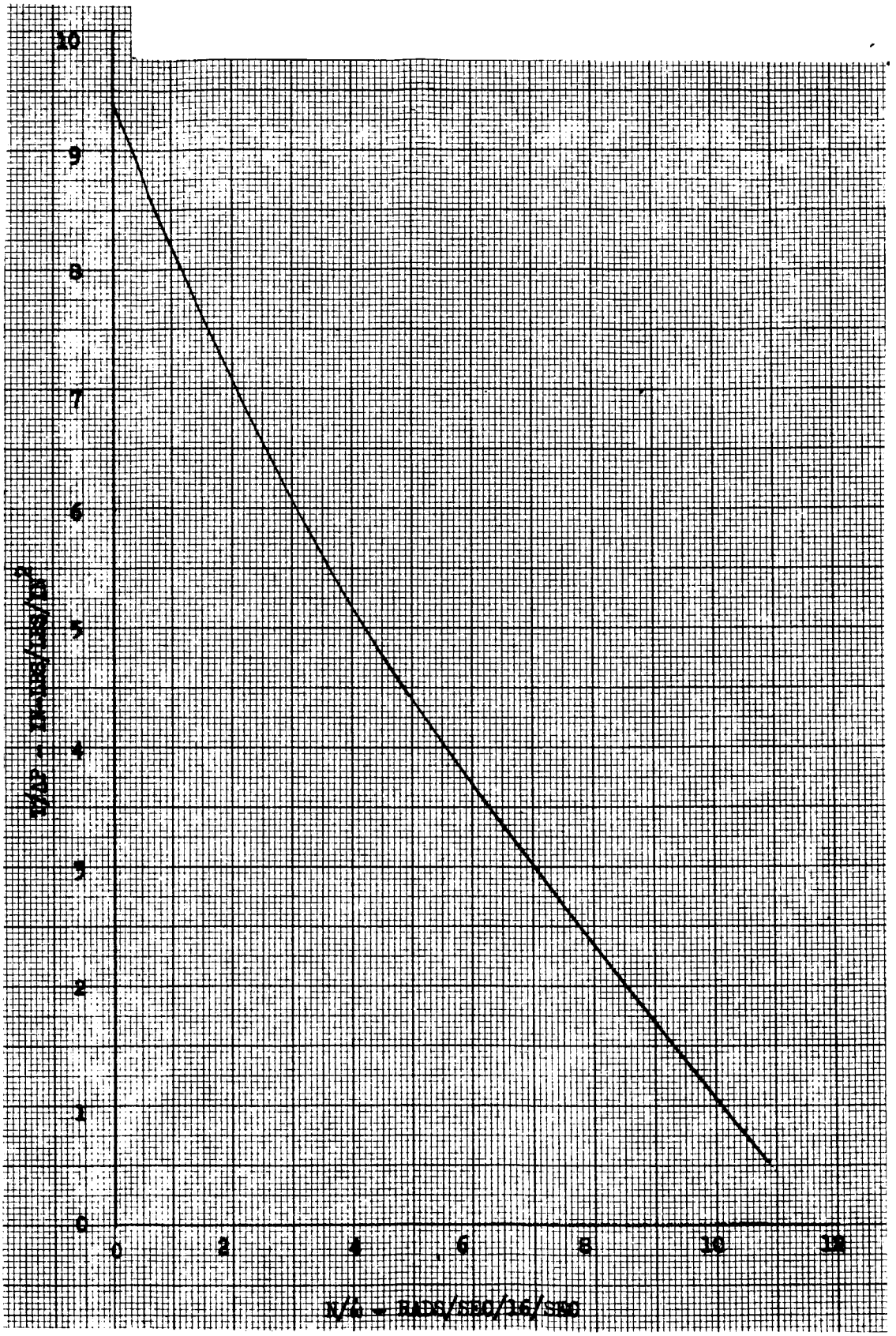


Figure 21. Hydraulic Turbine Torque Map

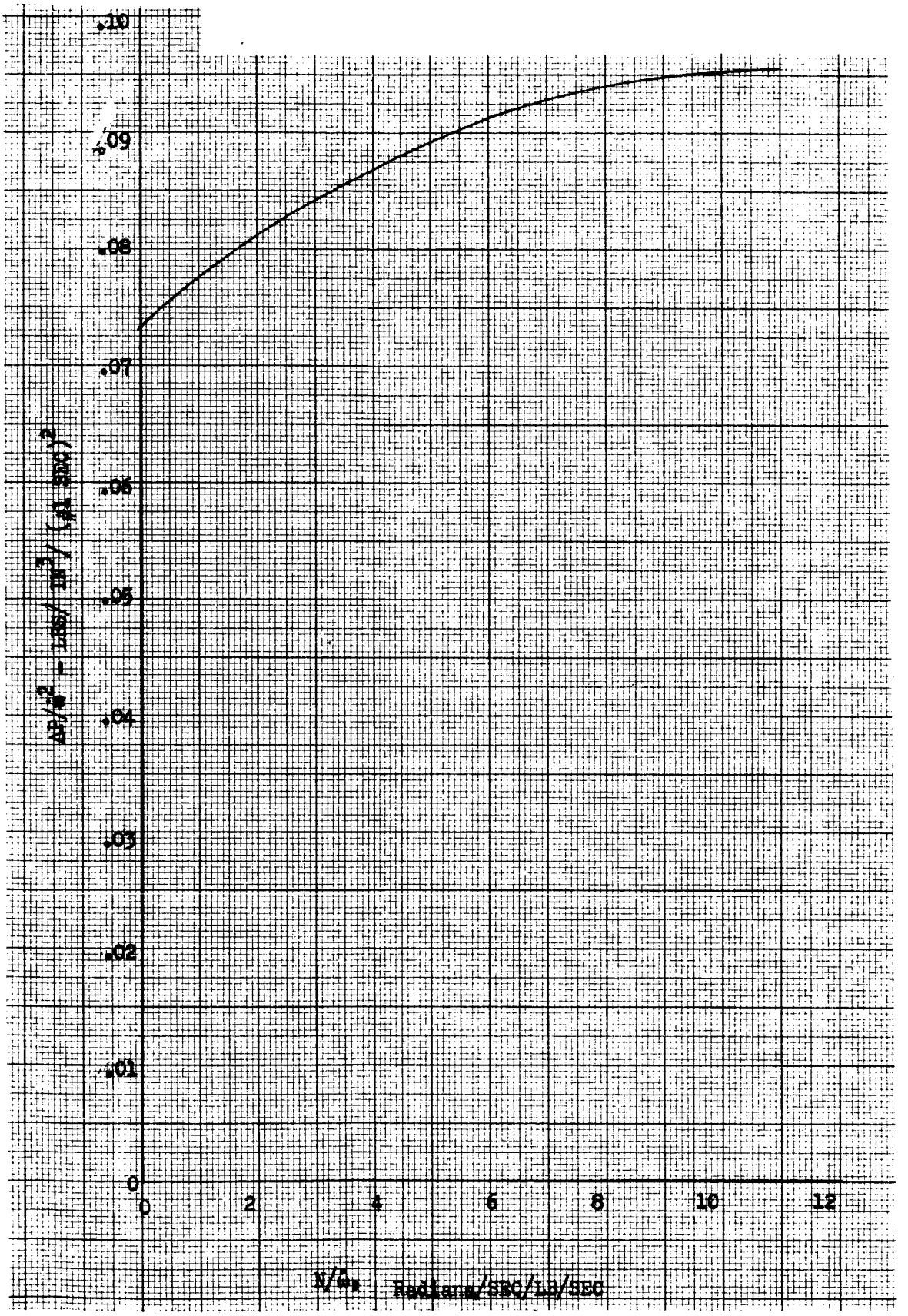


Figure 22. Hydraulic Turbine Flow Characteristic

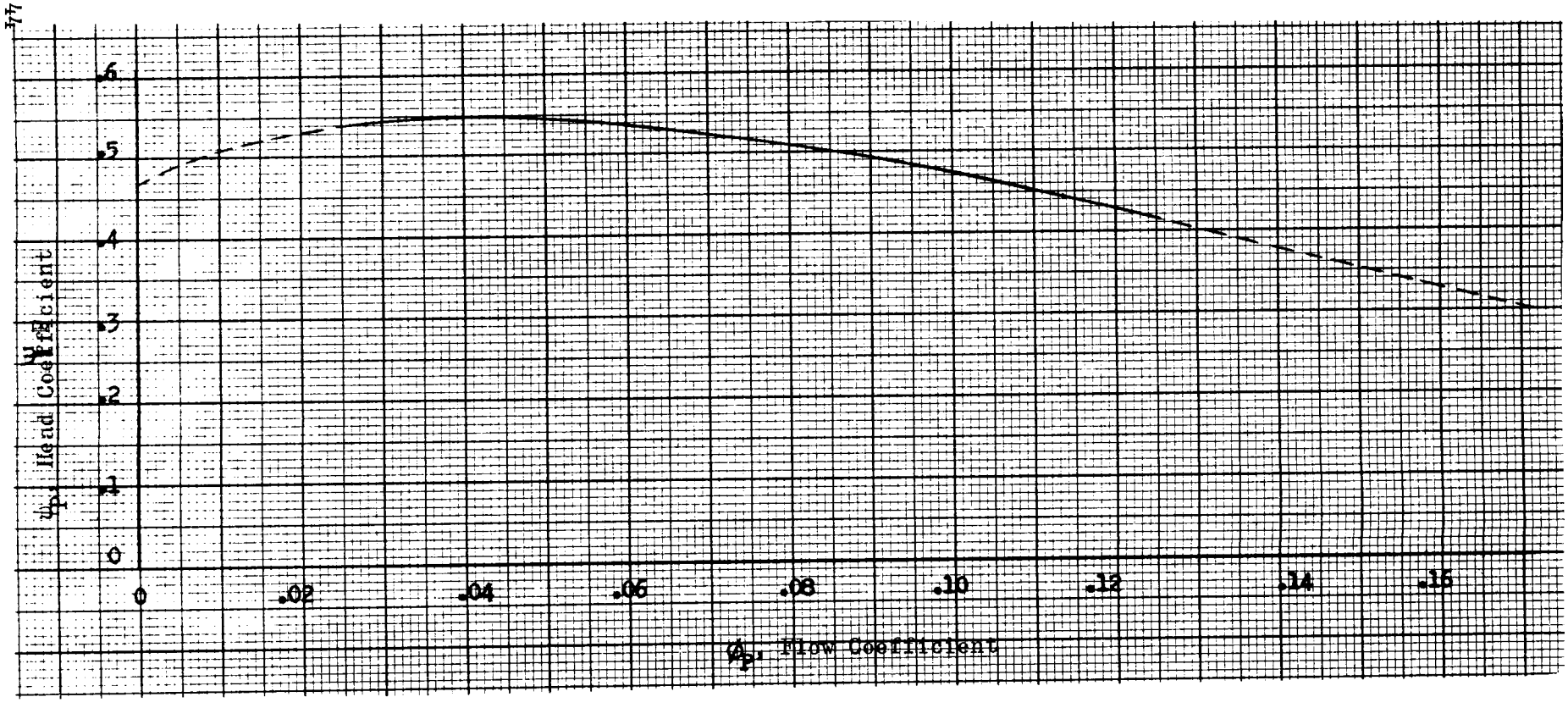


Figure 23. Main Pump Head Capacity Characteristic

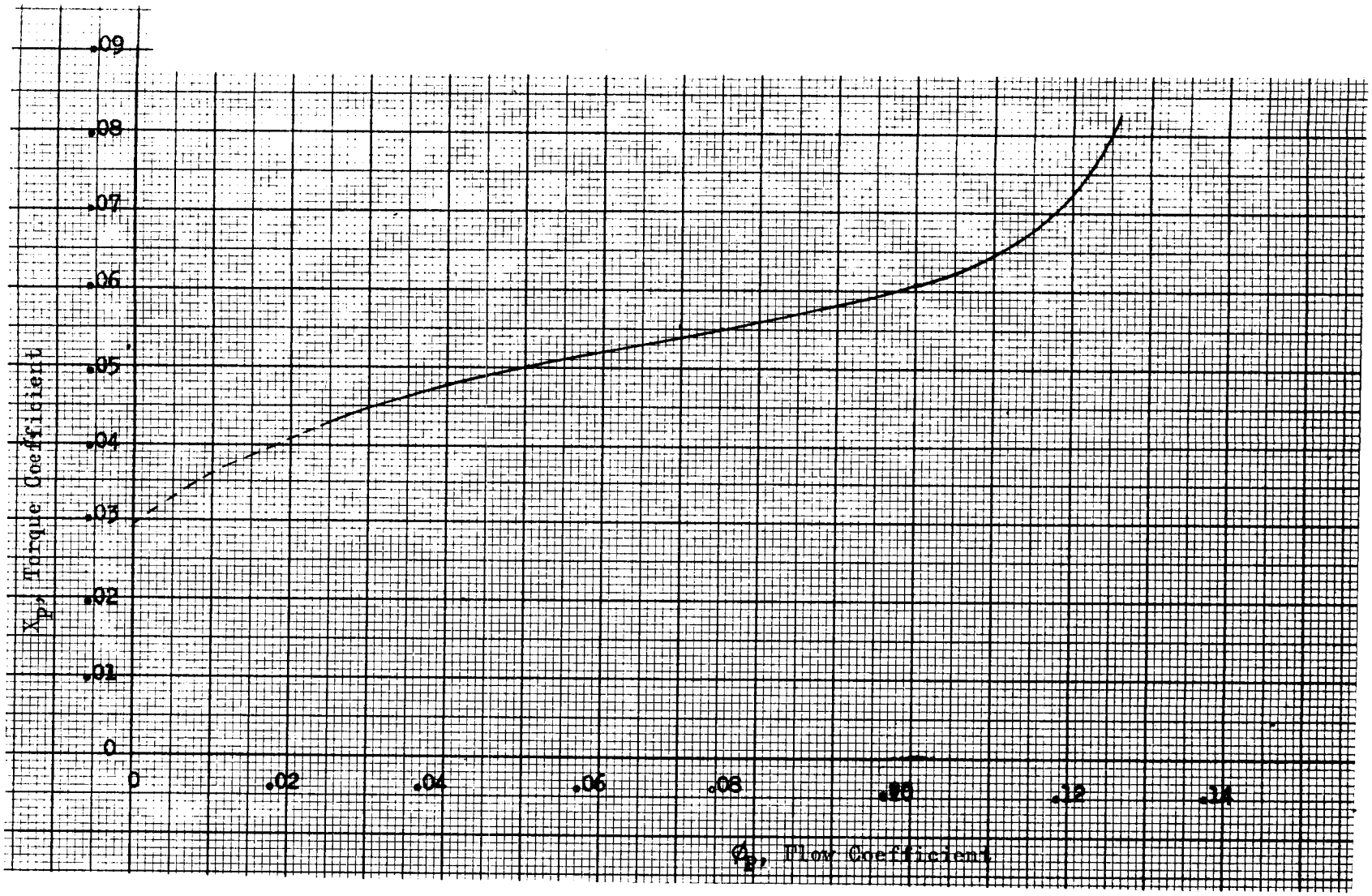


Figure 24. Main Pump Torque Capacity Characteristic

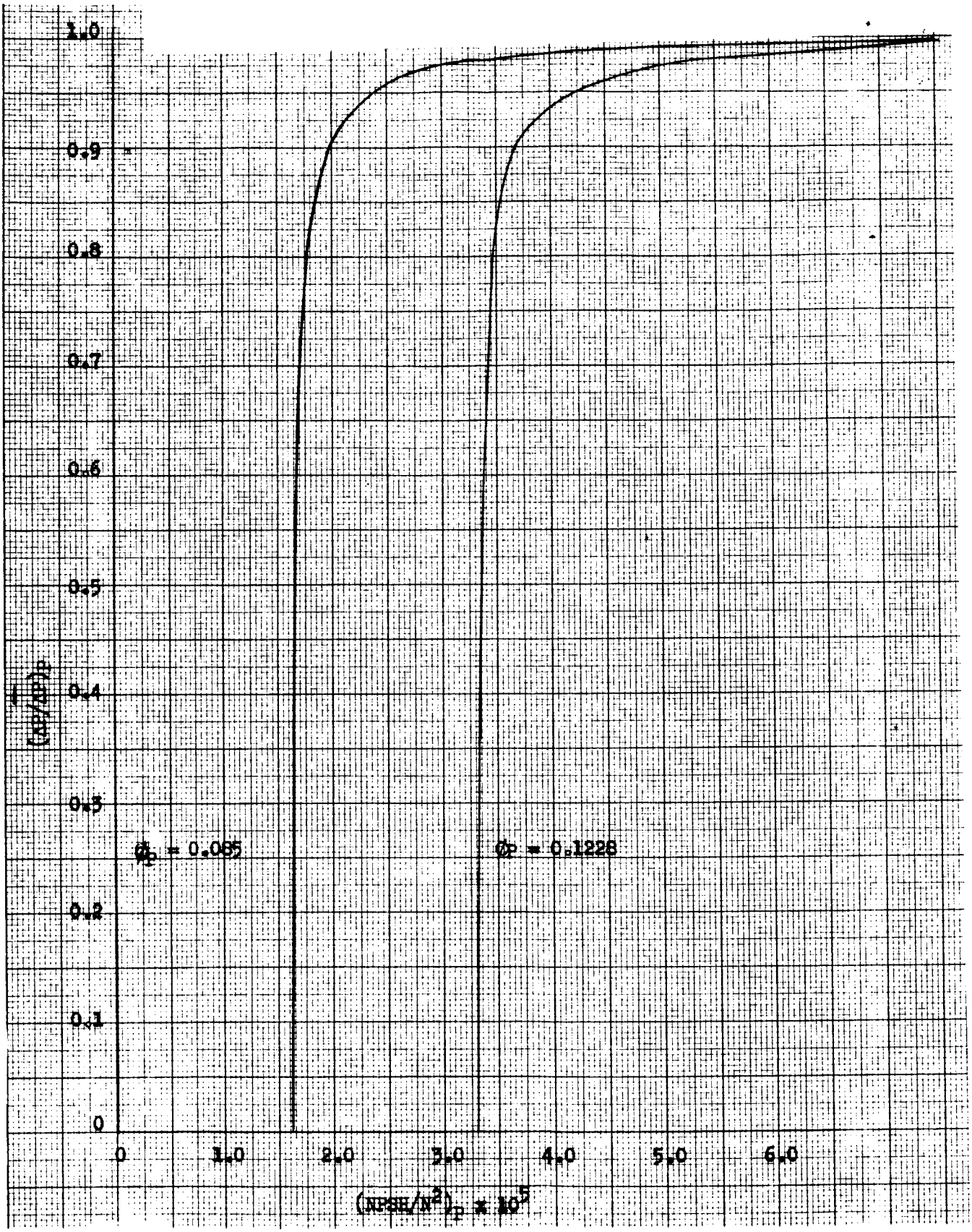


Figure 25. Main Pump, Cavitation Correction

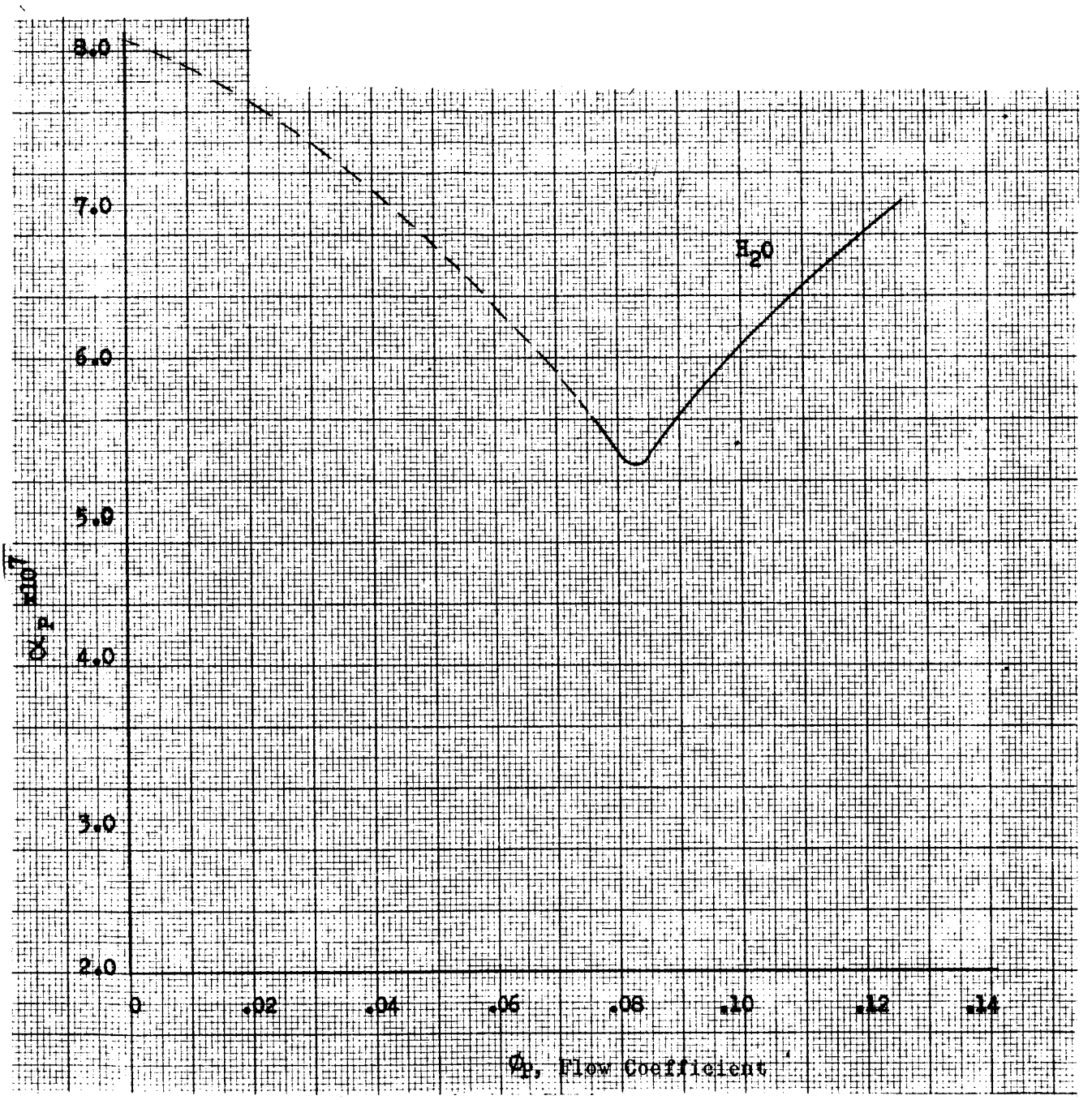


Figure 26. Main Pump Cavitation Correction Parameter

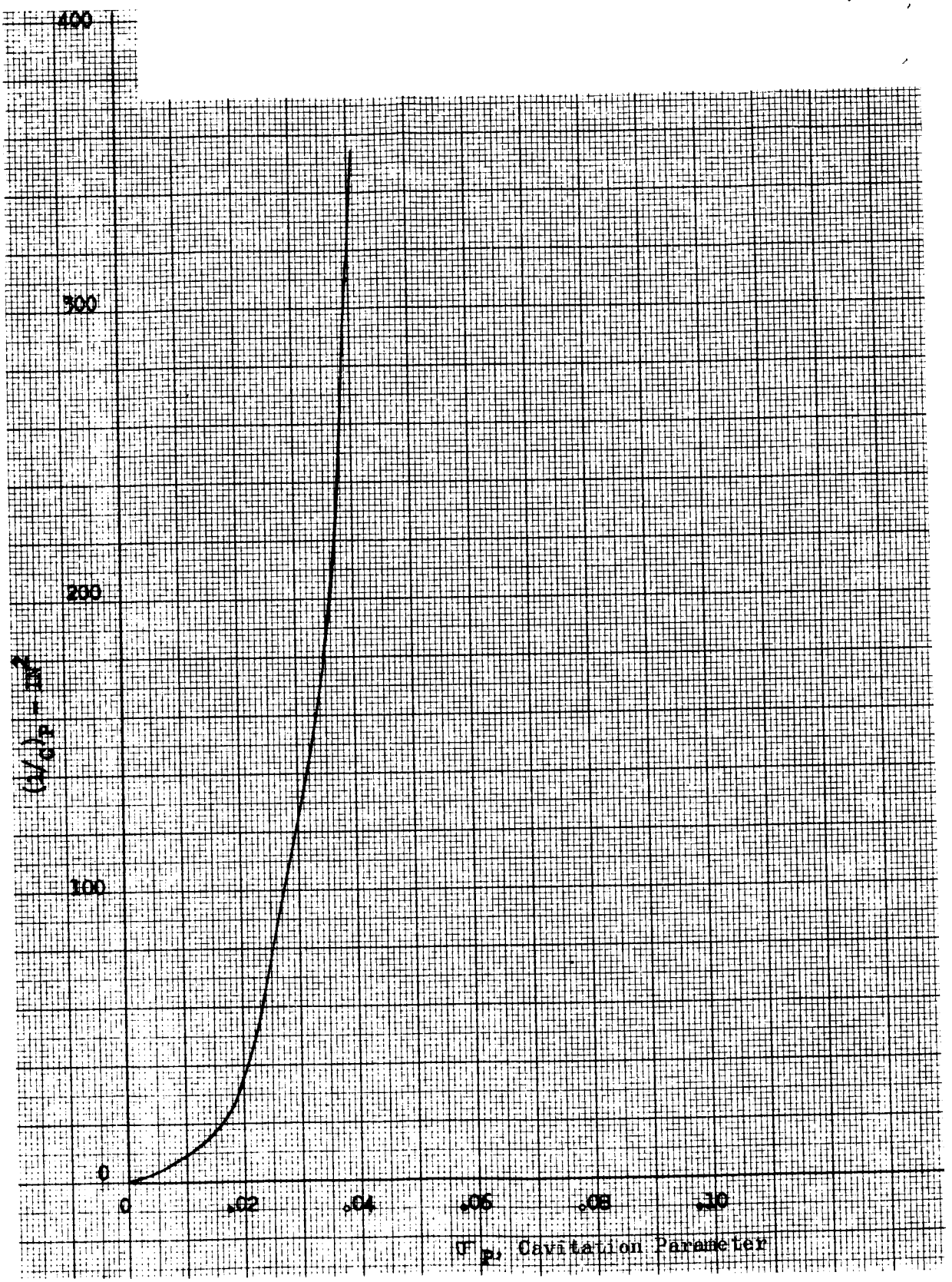


Figure 27. Main Pump Inlet Compliance

FEED LINE DESCRIPTION

Three methods of representing the feed lines were used on the line length under consideration. These are the time delay (wave equation), lumped parameter, and modal.

The digital model uses the time delay and lumped parameter representations, while the analog model uses a combination of all three.

The time delay representation is satisfactory for all frequencies; the frequency range of the modal representation is dependent on the number of modes used, while the lumped parameter (the simplest representation) is satisfactory for lines whose length is less than approximately 1/8 wavelength of an acoustic mode at the maximum desired frequency. For water at 50 cps, 1/8 wavelength is approximately 11 feet.

On the digital model, the lumped parameter description was used for the 2-foot section of line from the main pump discharge to the turbine feed line junction and for the turbine feed line. While the turbine feed line is approximately 20 feet long, it was believed that for the transient studies, where no external pulsing is present and the generated oscillations are low frequency, this was satisfactory. The remainder of the feed lines were represented by the time delay equations.

The analog model used the lumped parameter representation for the 2-foot section from the pump discharge to the turbine line junction, a time delay representation for the pump coupling line when the preinducer is remotely located from the main pump, and the modal description for the remainder of the lines. In general, the modal method, on the analog computer, results in a more stable solution than the time delay method and, consequently, was used when sufficient computer equipment was available.

PREINDUCER DESCRIPTION

The complete preinducer simulation includes noncavitating performance maps of head and torque coefficients versus flow coefficient, a cavitation correction factor expressing the percent of performance loss as a function of NPSH divided by speed squared, and the fluid dynamics represented by the inlet and outlet compliances and inertance.

Performance of the preinducer was represented by curves describing the noncavitating head- and torque-capacity characteristics corrected for cavitation. The noncavitating performance curves were determined from the steady-state maps and described as a head coefficient (proportional to generated pump head divided by speed squared), and a torque coefficient (proportional to required pump torque divided by speed squared) versus a flow coefficient (proportional to flowrate divided by speed). The cavitation correction factor is a ratio of actual to noncavitating generated pump pressure versus pump NPSH divided by speed squared. The curves expressing this ratio, shown in Fig. 19, were estimated from 2-percent head loss data on the J-2 fuel pump inducer and 100-percent head loss calculations. The curves of Fig. 19 were fitted, for use in the computer models, with the equation for an equilateral hyperbola. This equation is of the form $X \cdot Y = \alpha$ where $X = (1 - \Delta P/\Delta \bar{P})$ and $Y = (NPSH/N^2 - (NPSH/N^2)_o)$, $(NPSH/N^2)_o$ being taken as the value of $NPSH/N^2$ at $\Delta P/\Delta \bar{P} = 0.0$. α was calculated from the data of Fig. 11 and is shown plotted in Fig. 20, the dashed portion of the curve being an extrapolation for use in the computer models.

Representation of the preinducer dynamics was patterned after the results of a J-2 Pogo analysis study presented in Rocketdyne Report R-6283 submitted to NASA under Contract NAS8-19, G.O. 8590. The results of this study indicated that the pump dynamics are associated with the inducer section of a pump and that a reasonable representation is two compliances separated by an inertance. This type of representation was used for the preinducer where values of the compliances and inertance were based on pump test data.

PUMP DESCRIPTION

The main pump representation includes only noncavitating performance maps (Fig. 23 and 24) and a cavitation correction factor shown in Fig. 25 and 26. Figures 25 and 26 were generated in the same manner as the preinducer cavitation curves based on the 2-percent head loss data of Fig. 9 and 100-percent head loss calculations. This representation also was based on the results of the previous study which indicated that the impeller section of the pump followed the noncavitation performance curves. In the case of the remote-coupled pumps, allowance is made for a compliance (Fig. 27) at the pump inlet. It also should be noted that when speed is used as an input to the main pump, the main pump torque is not required.

HYDRAULIC TURBINE DESCRIPTION

The representation of the hydraulic turbine is based on performance curves giving the developed torque divided by turbine pressure drop and turbine pressure drop divided by flowrate squared as functions of turbine speed divided by flowrate. The performance curves (Fig. 21 and 22) were supplied from the output of the steady-state mapping programs. These curves then were either curve fitted or used as point data with linear interpolation between points in the computer programs.

SYSTEM DATA

Determination of the remainder of the equation coefficients involved line lengths and diameter, fluid sonic velocity, rated operating point of the system, calculated moment of inertia of the preinducer and estimates of the compliance and inertance values from previous test programs. Table 1 presents the test system line and component data not shown as curves. The operating point data for the preinducer test system are presented in Table 2.

TABLE 1

SYSTEM DATA

Description	Value
1. Feed lines	
a. Tank exit to facility interface	
1. Length, inches	78
2. Diameter, inches	9
3. Acoustic velocity, ft/sec	3670
b. Facility interface to inducer inlet	
1. Close coupled	
a. Length, inches	264
b. Diameter, inches	10
2. Remote coupled	
a. Length, inches	84
b. Diameter, inches	10
3. Acoustic velocity, ft/sec	4090
c. Pump coupling line	
1. Length, inches	180
2. Diameter, inches	10
3. Acoustic Velocity, ft/sec	4090
d. Main pump discharge to tapoff junction	
1. Length, inches	24
2. Diameter, inches	4
e. Turbine feed line	
1. Length, inches	114
2. Diameter, inches	4
3. Length, inches	136
4. Diameter, inches	2

TABLE 1

(Concluded)

Description	Value
f. Pump discharge line	
1. Length, inches	96
2. Diameter, inches	6
3. Acoustic velocity, ft/sec	4205
g. Facility return line	
1. Length, inches	3720
2. Diameter, inches	8
3. Acoustic velocity, ft/sec	3670
2. Preinducer pump	
a. Radius, inches	4.875
b. Area, sq in.	64.25
c. Moment of inertia, in.-lb-sec^2	0.24
3. Main Pump	
a. Radius, inches	5.1
b. Area, sq in.	22.9
c. Moment of inertia, in.-lb-sec^2	1.0
4. Water density, lb/cu in.	0.0361
5. Tube bundle resistance, sec^2/in.^{5}	3.735×10^{-6}
6. Inducer-turbine valve resistance, sec^2/in.^{5}	5.88×10^{-4}
7. Discharge line valve resistance, sec^2/in.^{5}	2.437×10^{-4}

TABLE 2

TEST SYSTEM OPERATING POINT

Parameter	Value
Tank Pressure, psia	15
Preinducer Inlet Pressure, psia	4
Preinducer Outlet Pressure, psia	79.5
Main Pump Outlet Pressure, psia	707.5
Turbine Tapoff Junction Pressure, psia	697.5
Turbine Inlet Pressure, psia	603.8
Preindueer Speed, rpm	3930
Main Pump Speed, rpm	7560
Inducer Flowrate, lb/sec	326
Hydraulic Turbine Flowrate, lb/sec	76
Main Pump Flowrate, lb/sec	402

COMPUTER PROGRAMS

To provide a solution to the system of equations, two computer programs were prepared, one for solution on a digital computer and one for solution on an analog computer. Initially, the two programs were used as a check against each other. When both programs gave comparable results, parametric studies were made. The analog program was used for analysis pertaining to the water test facility while the digital program was used to predict performance for an engine application of a hydraulic turbine driven preinducer.

DIGITAL MODEL

The digital computer model was programmed using an IBM application program called System/360 Continuous Sytem Modeling Program (360A-CX-16X). Using this approach it was necessary to program only the statements involved in the problem along with the input data.

Listings of the problem solution portion of the program and a function called DLAY, for use with the time delay equation, are shown in the appendix for the water test facility close- and remote-coupled preinducer configurations. With a few exceptions, the coding is nonprocedural; that is, the order of solution is not dependent on the order in which the statements appear. The CSMP program translates the problem statements so that the proper order of solution is attained. The exceptions are those statements contained in the NO SORT and PROCEED sections. The table of Output Variable Sequence found at the end of the listing gives the sorted sequence.

The coding of the statements is very similar to FORTRAN and can be understood by anyone familiar with the FORTRAN language. The component performance characteristics expressed by curves use a CSMP function called AFGEN. The input for this function is a series of x and y coordinate values taken from the curves. The function determines the value of the

dependent variable by linear interpolation at the desired value of the independent variable. The remainder of the input data is supplied in statements preceded by the word PARAM.

Various methods of integration are available with the CSMP program which may be selected at the user's option. Both Simpson's and the trapezoidal method were used in running the model.

The program solves the equations as a function of time and provides printed and plotted output. A sample of these forms of output is shown in the appendix. To use the program as listed, the complete CSMP application program and manuals must be obtained from the IBM Corporation.

ANALOG MODEL

The equations for the analog model were mechanized on an Applied Dynamics AD-288 computer. This computer has bipolar amplifiers; therefore, both a positive and negative output are available from each amplifier. This is reflected in the program diagram shown in the appendix.

This program uses primarily second-order curve fits of the pump and turbine performance curves, and a modal representation for the feed lines. In the case of the remote-coupled preinducer, a time delay simulation is used for the coupling line where use is made of prepackaged time delay circuits installed at the Rocketdyne analog computing facility.

PROGRAM COMPARISON

One of the reasons for developing both an analog and a digital model of the system was to cross check the results of both programs to assist in eliminating errors. The final result of this cross checking is shown in Fig. 28 through 33 which present a comparison of the analog and digital results for the close- and remote-coupled configuration. The main pump, in all cases, was driven with a linear, 3-second ramp torque input. It is believed that the comparison is sufficiently close to justify using the results from either program. The differences are attributed to a slightly lower speed balance used in the digital program.

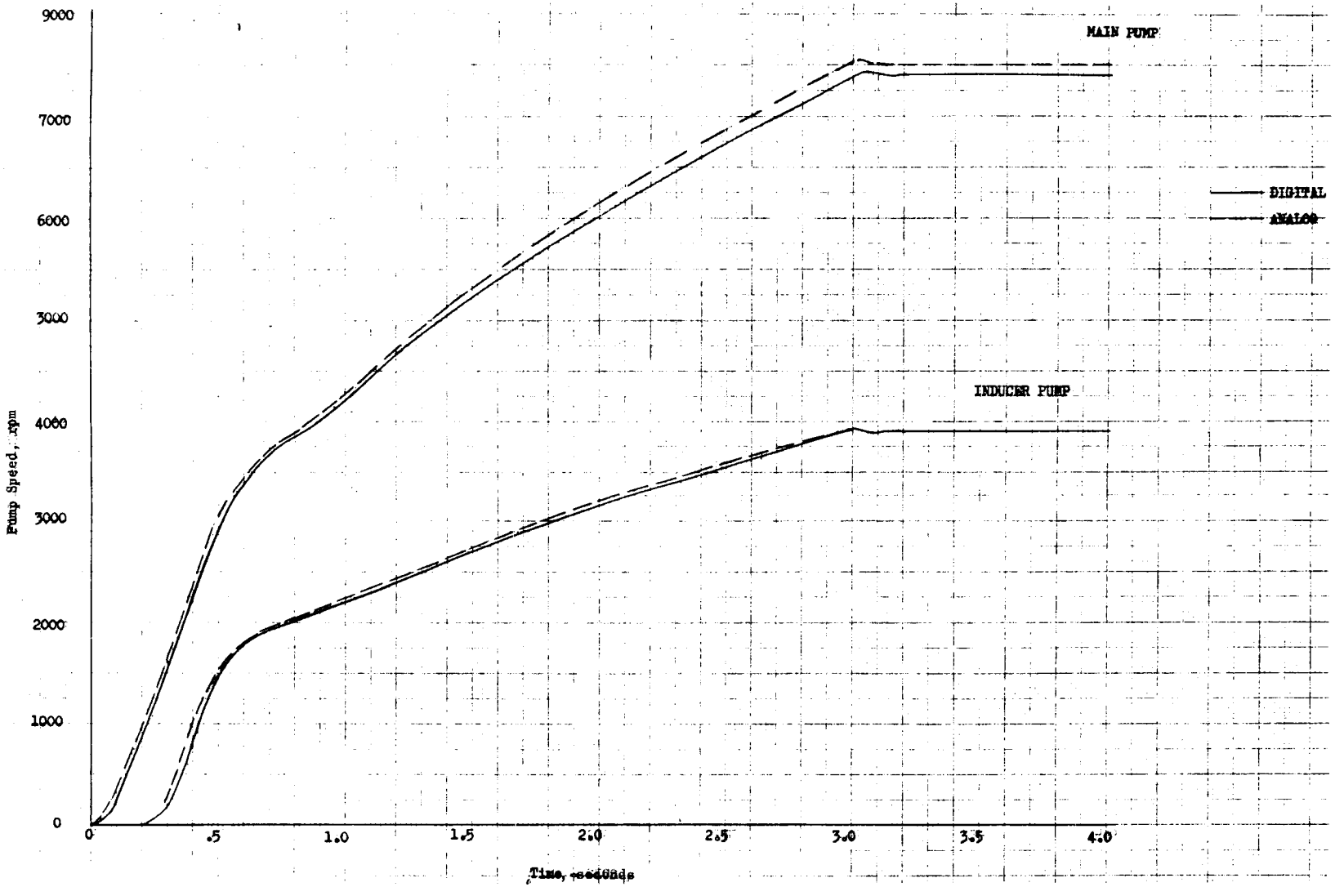


Figure 28. Inducer and Main Pump Speed, Close-Coupled Configuration

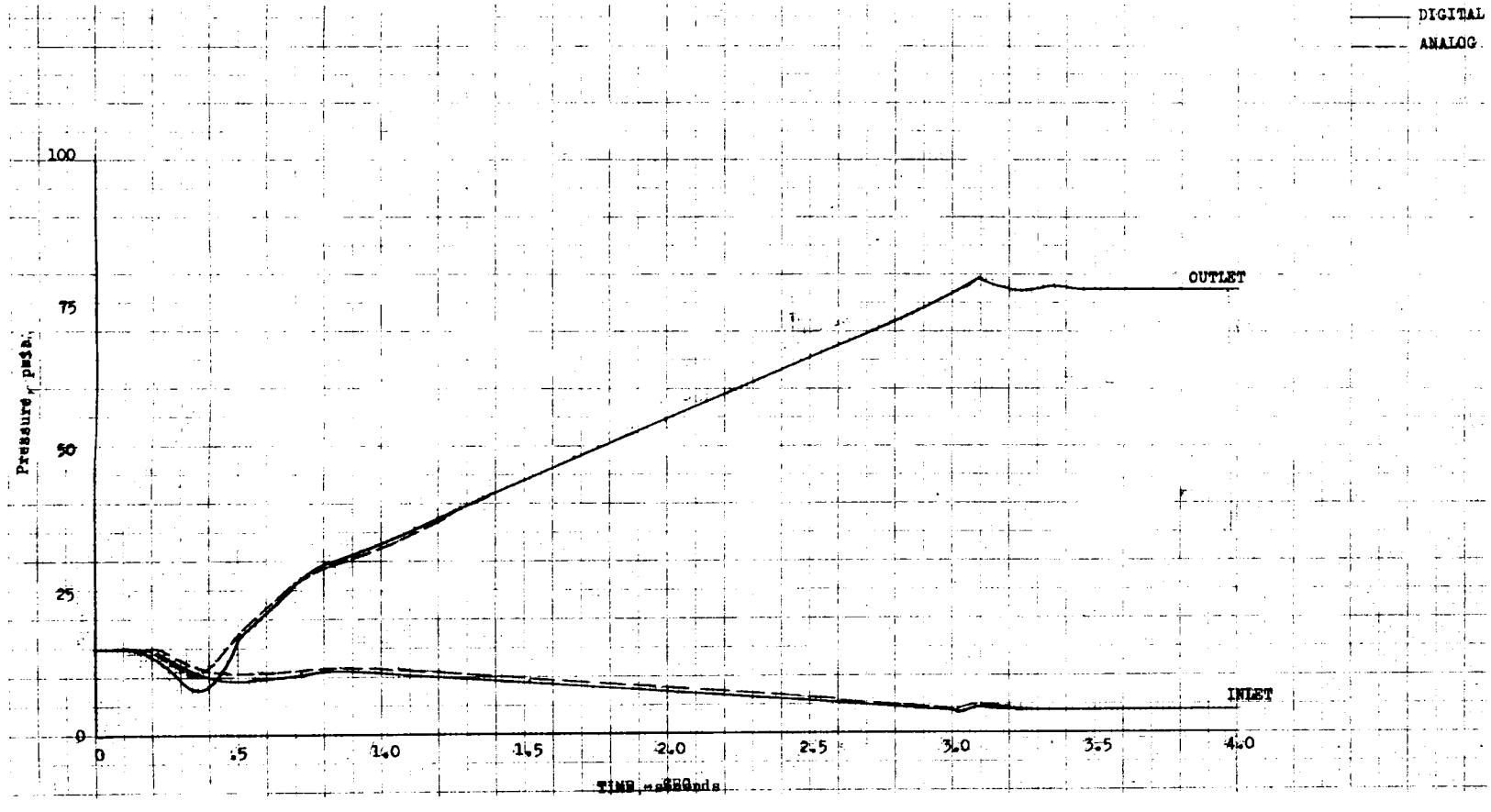


Figure 29. Inducer Pump Pressures, Close-Coupled Configuration

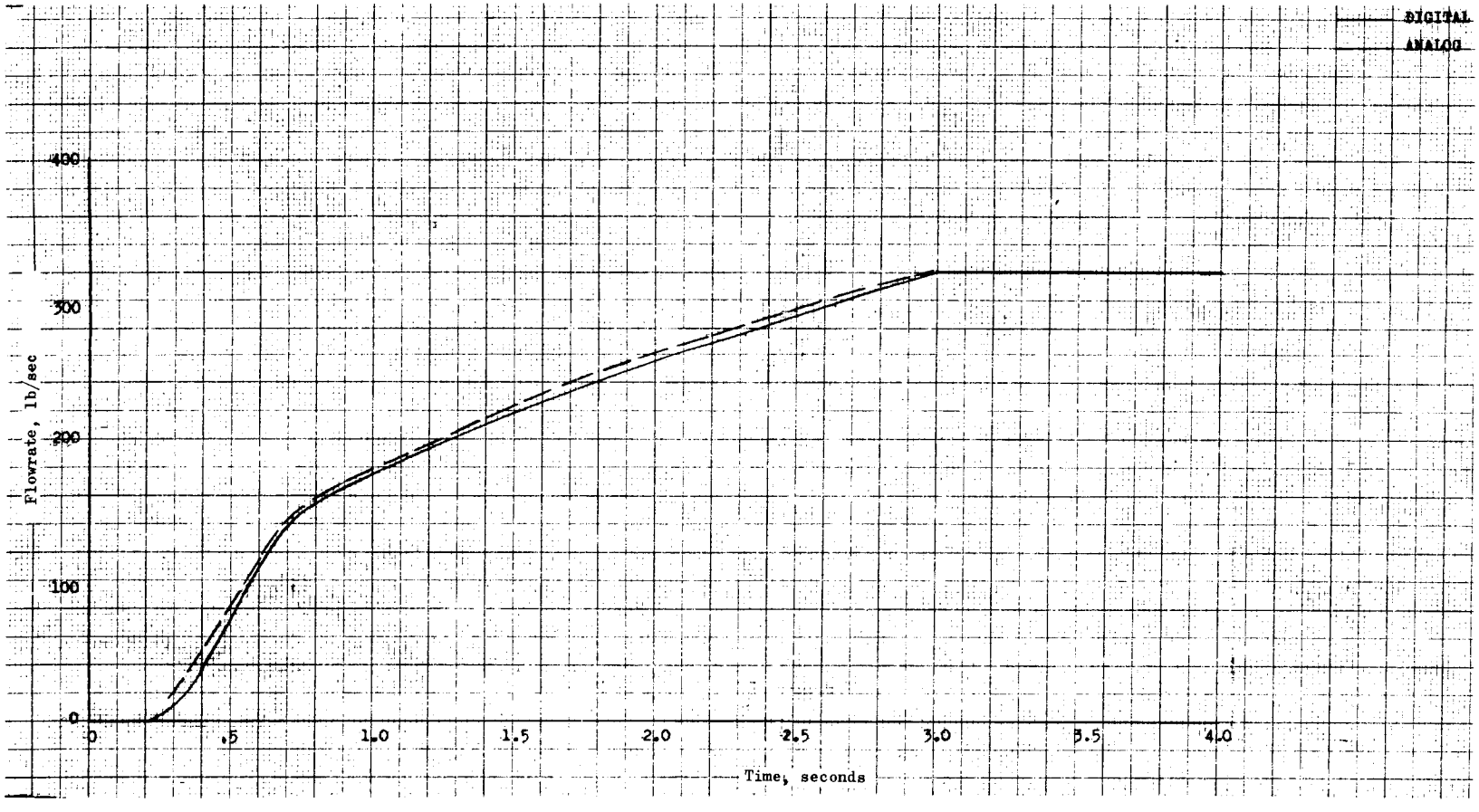


Figure 30. Inducer Pump Flowrate, Close-Coupled Configuration

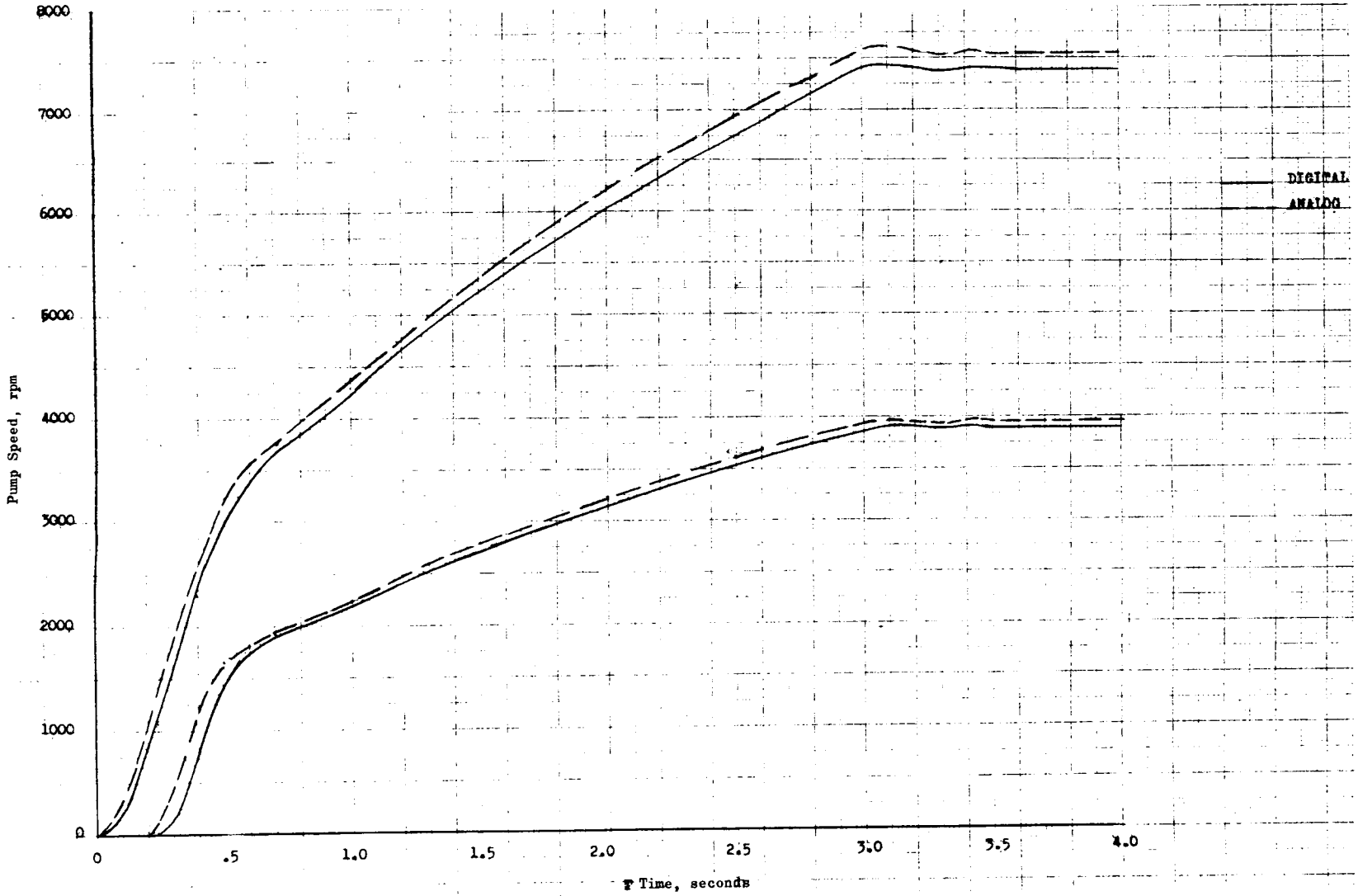


Figure 31. Inducer and Main Pump Speed, Remote-Coupled Configuration

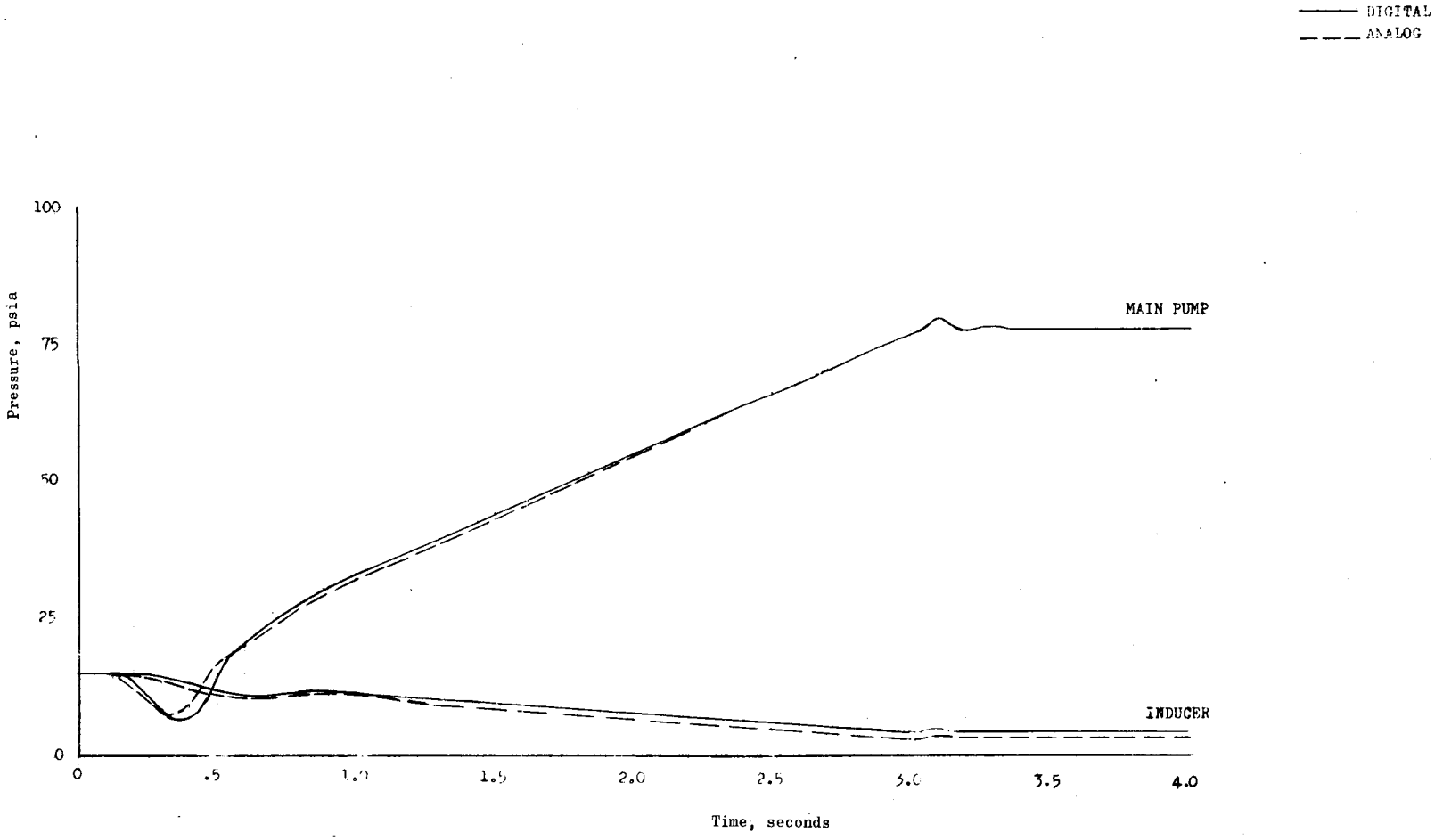


Figure 32. Pump Inlet Pressures, Remote-Coupled Configuration

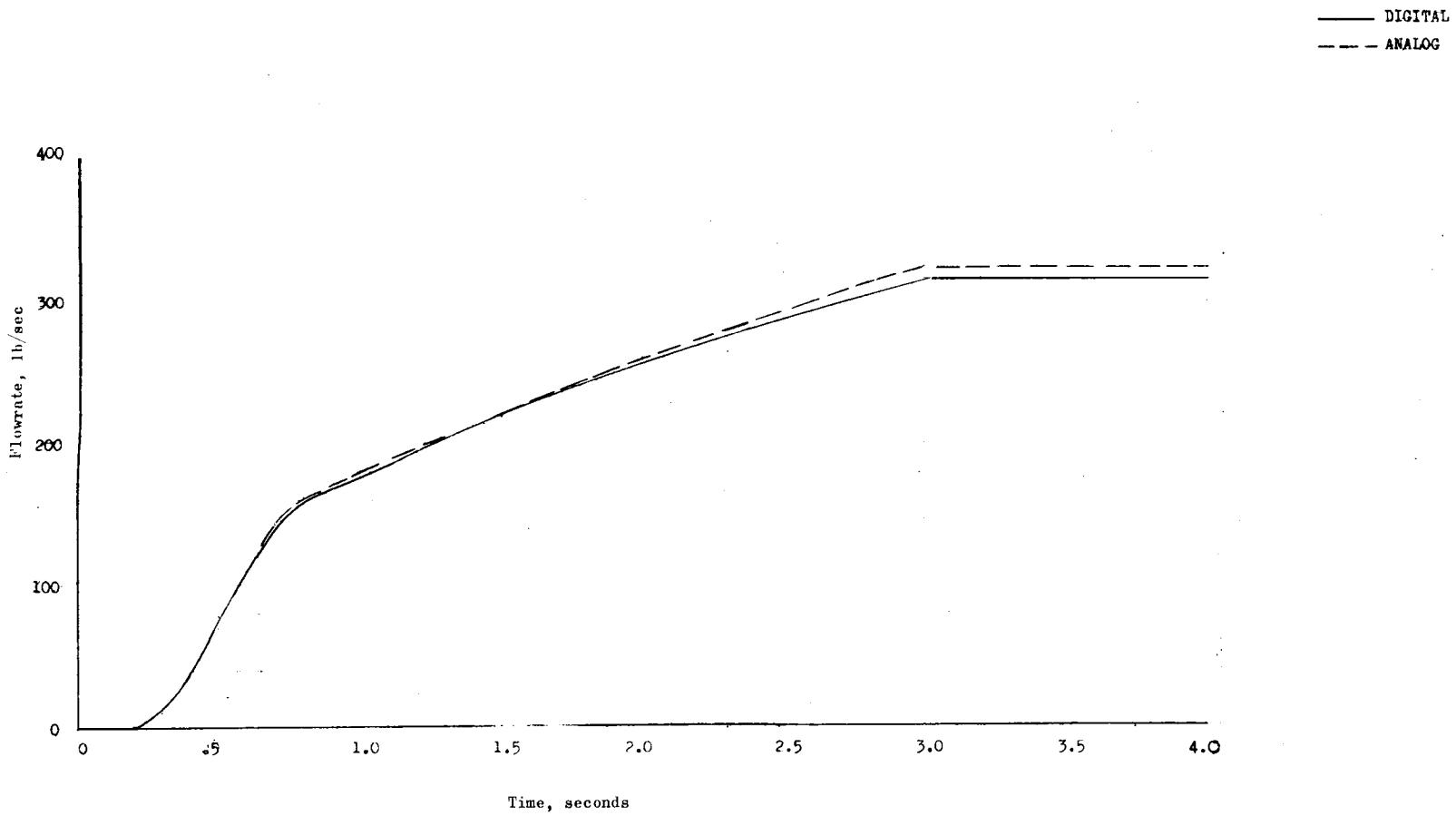


Figure 33. Inducer Pump Flowrate, Remote-Coupled Configuration

PARAMETRIC STUDIES

INTRODUCTION

A series of parametric studies was conducted, using the analog and digital computer models, to evaluate the effect of selected parameters on the transient performance of the simulated pump system and to predict the operation of hydraulic turbine driven preinducers in an LH_2 and LO_2 rocket engine feed system.

The studies can be grouped into three areas covering: (1) variations in the water test preinducer hardware and test system parameters, (2) predictions of the test program start and throttling performance, and (3) the use of preinducers in an engine feed system.

The parameter variations in group 1 were run to establish the type of hydraulic turbine which should be designed and to determine what effect selected preinducer parameter and test stand line sizes might have on the system starting performance. In this area, the following parameters were considered:

1. A two-stage vs three-stage hydraulic turbine
2. Increased and decreased preinducer moment of inertia
3. Increased diameter of the pump coupling line for the remote-located preinducer
4. Resistance of the hydraulic turbine feed line
5. Reduced turbine feed line fluid inertia
6. Low-head preinducer

The test program predictions cover 0- to 100-percent pump speed rates from 1.5 to 4.0 seconds at nominal and 120-percent pump Q/N and throttling performance from 100 to 65 percent and 65 to 100 percent at various throttling rates. The rates were taken from the proposed test plan and form a starting point for comparing the test and model performance.

The third group considers the use of preinducers in an engine feed system. The feed system used represents the Saturn S-IVB and the propellants being pumped are liquid hydrogen and liquid oxygen.

PARAMETER SURVEY

The first series of studies involved variations in the preinducer test hardware and test system configuration. To assess the effects of these variations the following reference condition was chosen:

1. High-head preinducer pump
2. Three-stage hydraulic preinducer turbine
3. J-2 LO_2 main pump
4. Run tank pressure of 15 psia
5. Tank outlet resistance to give 4 psia, 8-foot NPSH at the preinducer inlet at rated flow
6. Turbine inlet valve and discharge valve resistance set to give rated flow conditions
7. Three-second linear torque ramp input to the main pump

Data obtained from the analog computer model for the reference starts are presented in Fig. 34 and 35 for the close and remote preinducer locations, respectively.

The primary area of interest for this type of start is the initial depression in the main pump inlet pressure. The depression results from the inherent lag in the preinducer pump speed buildup due to the hydraulic turbine being driven by a feedback from the main pump. As the main pump is accelerated, flow is initiated through the discharge system. To accelerate the flow from the tank through the pumps, the preinducer inlet and outlet pressures must decrease. The drop in preinducer outlet pressure will decrease until sufficient head is generated by the speed

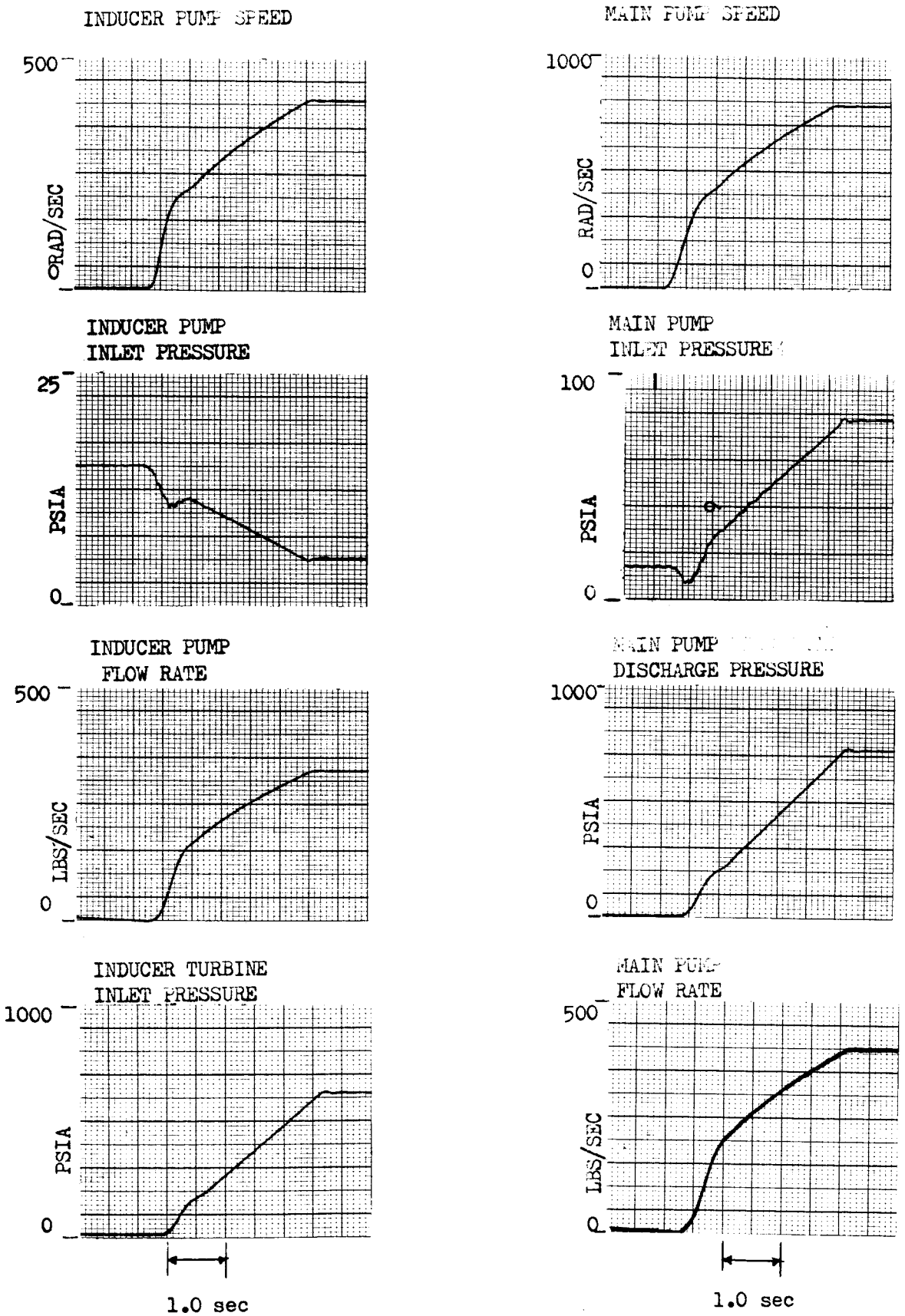


Figure 34. Close-Coupled Reference Start

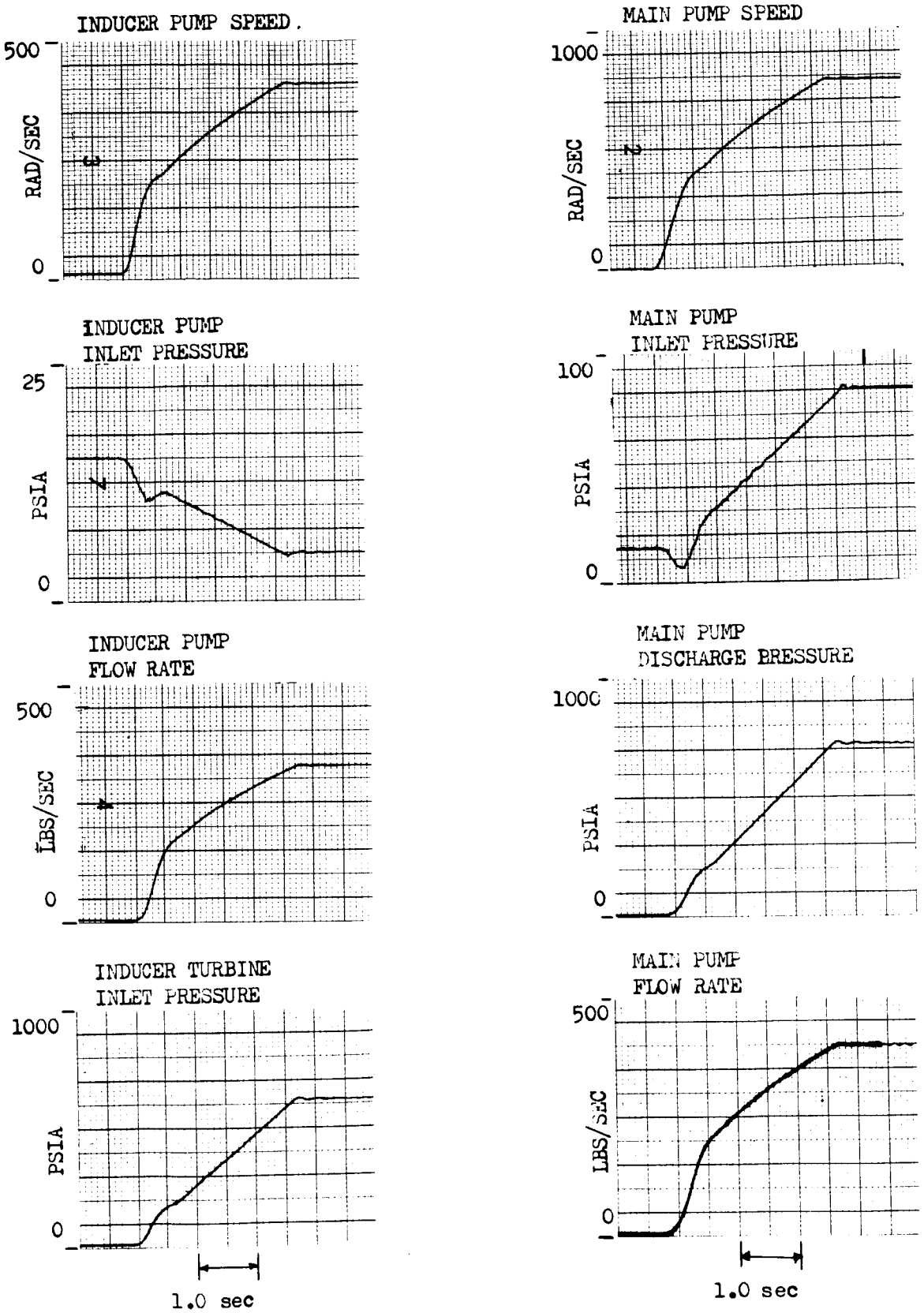


Figure 35. Remote-Coupled Reference Start

buildup of the preinducer. For the close-coupled configuration, the preinducer outlet and main pump inlet pressure are the same, while for the remote-coupled configuration, a section of line connects the preinducer outlet to the main pump inlet.

The effect of the depression in the preinducer discharge pressure is that as the tank pressure is lowered, the absolute pressure at the main pump inlet (due to the depression) decreases. If it reaches a low enough value, severe pump cavitation will result. Therefore, the difference between the tank pressure and minimum main pump inlet pressure has been used to compare the effect of the parametric variations. The pressure differences for the reference starts are 6 psi with a close-coupled preinducer and 8 psi with the remote-coupled preinducer. Comparing the curves of the inducer and main pump flowrates, it can be seen that the main pump flowrate is higher than the inducer pump flowrate, at any given time, the difference increasing to 78 lb/sec when steady-state operation is reached. This difference is the flowrate returned from the main pump discharge to drive the hydraulic turbine.

The performance curves for the hydraulic turbines, shown in Fig. 12 and 13, show the two-stage compared to the three-stage turbine has a higher torque-to-pressure drop ratio and a lower pressure drop-to-flowrate squared ratio for low values of the speed-to-flowrate ratio. The torque/ΔP curve suggests the possibility of the two-stage turbine producing higher low-speed torque and consequently, higher preinducer speed acceleration. The system performance of the two-stage turbine driving the preinducer, shown in Fig. 36 and 37, for the close- and remote-coupled preinducer, respectively, however, indicates that no significant improvement in the starting performance was achieved. This is due to the fixed inlet valve resistance in the turbine feed line required to balance the system for rated operation. The lower two-stage turbine resistance results in an increase in turbine flowrate which produces an increase in the inlet valve pressure drop resulting in a decrease in the turbine pressure drop compared to the three-stage turbine. The decrease in turbine pressure drop results in comparable turbine torques for both the two- and three-stage turbines, and thus, the same buildup characteristics.

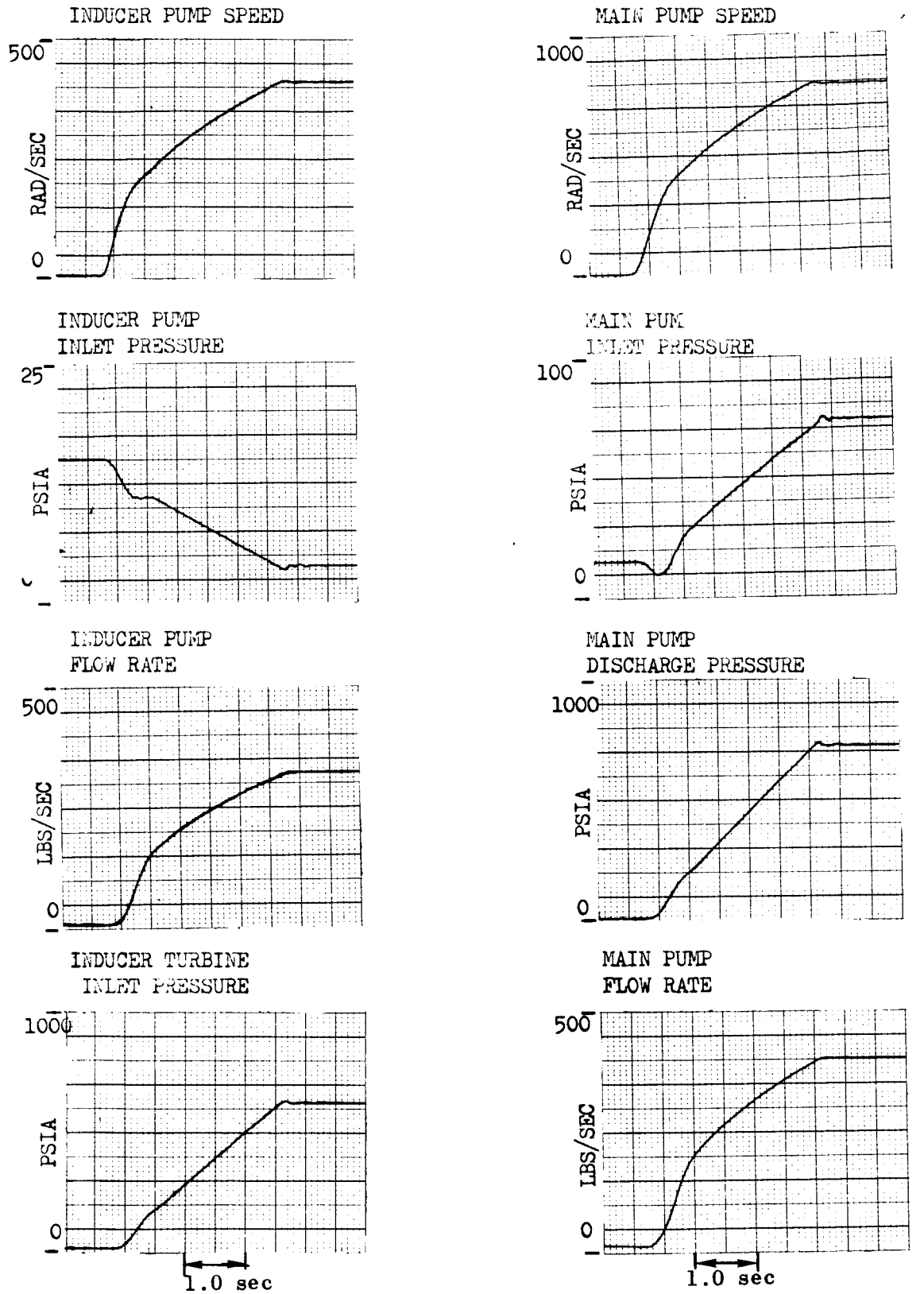


Figure 36. Close-Coupled, Two-Stage Turbine

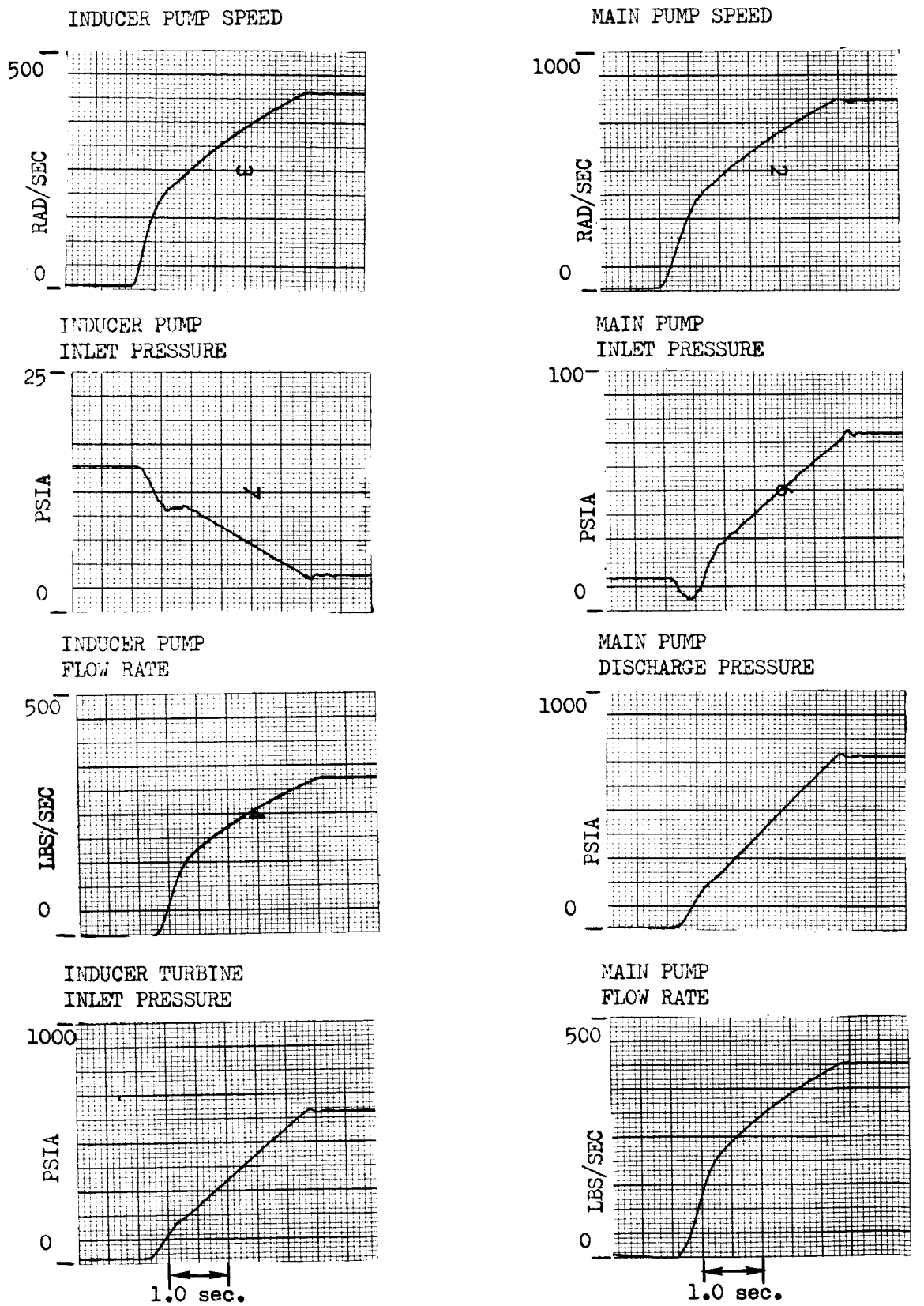


Figure 37. Remote-Coupled Two-Stage Turbine

For determining the effect of the preinducer moment of inertia, values of 0.1 and 3.0 times the design value of 0.24 in.-lb-sec^2 were used. The lower value of inertia does not represent any usable material. The high value of inertia could represent a preinducer made from K-monel. The results (Fig. 37 through 42) indicate a significant effect; the low moment of inertia reduced the main pump inlet pressure depression to about 2 and 5 psi below tank pressure for close- and remote-coupled preinducers, respectively, while the high inertia increased the depression to 12 and 14 psi, respectively. This indicates that care should be taken in the design and selection of materials for an engine preinducer to minimize the rotor moment of inertia.

The pump coupling line between the pump inlet and the preinducer outlet is used only with the remote-coupled preinducer configuration. Increasing this line area reduces the fluid inertia term which is proportional to the line length divided by the line area. The coupling line area was doubled; this resulted in a main pump inlet pressure depression of about 6.5 psi, as shown in Fig. 42. This is a significant change from the 8-psi depression of the reference case.

A variation of ±10 percent in inducer inlet line resistance was analyzed to determine the effect of a system balancing error. These results are presented in Fig. 43 through 46; they indicate no effect upon the minimum pump inlet pressure and only a very slight effect (less than 30 rpm) on the preinducer running speed. Consequently, this does not appear to be a critical item from the standpoint of water testing.

To determine the effect of the size of the turbine feed line, the length was halved and the area was doubled, which resulted in reducing the fluid inertia by a factor of 4. The results, shown in Fig. 47 and 48, indicate little, if any, effect. Therefore, for the test system, this is not a significant factor.

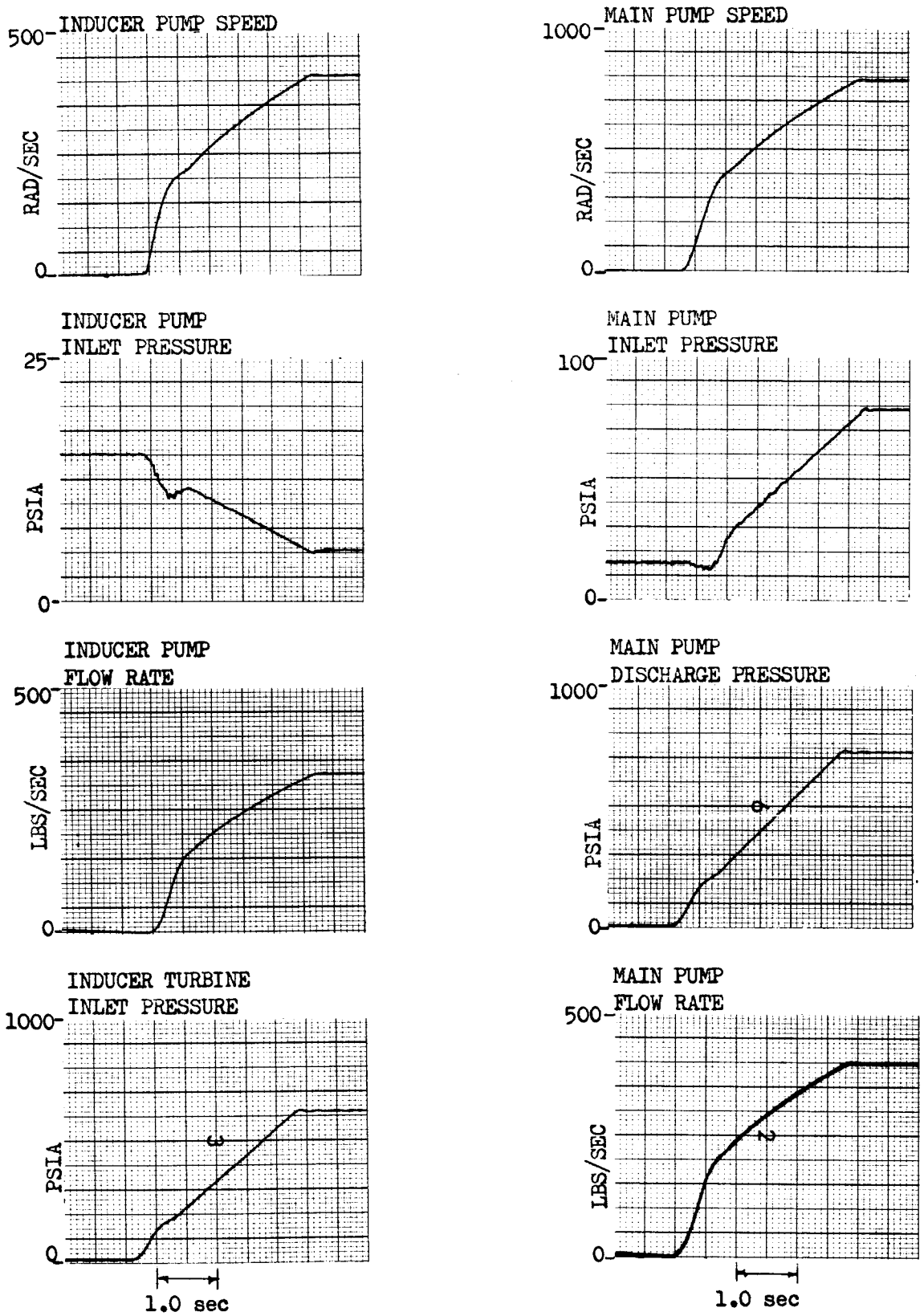


Figure 38. Close-Coupled Low Moment of Inertia

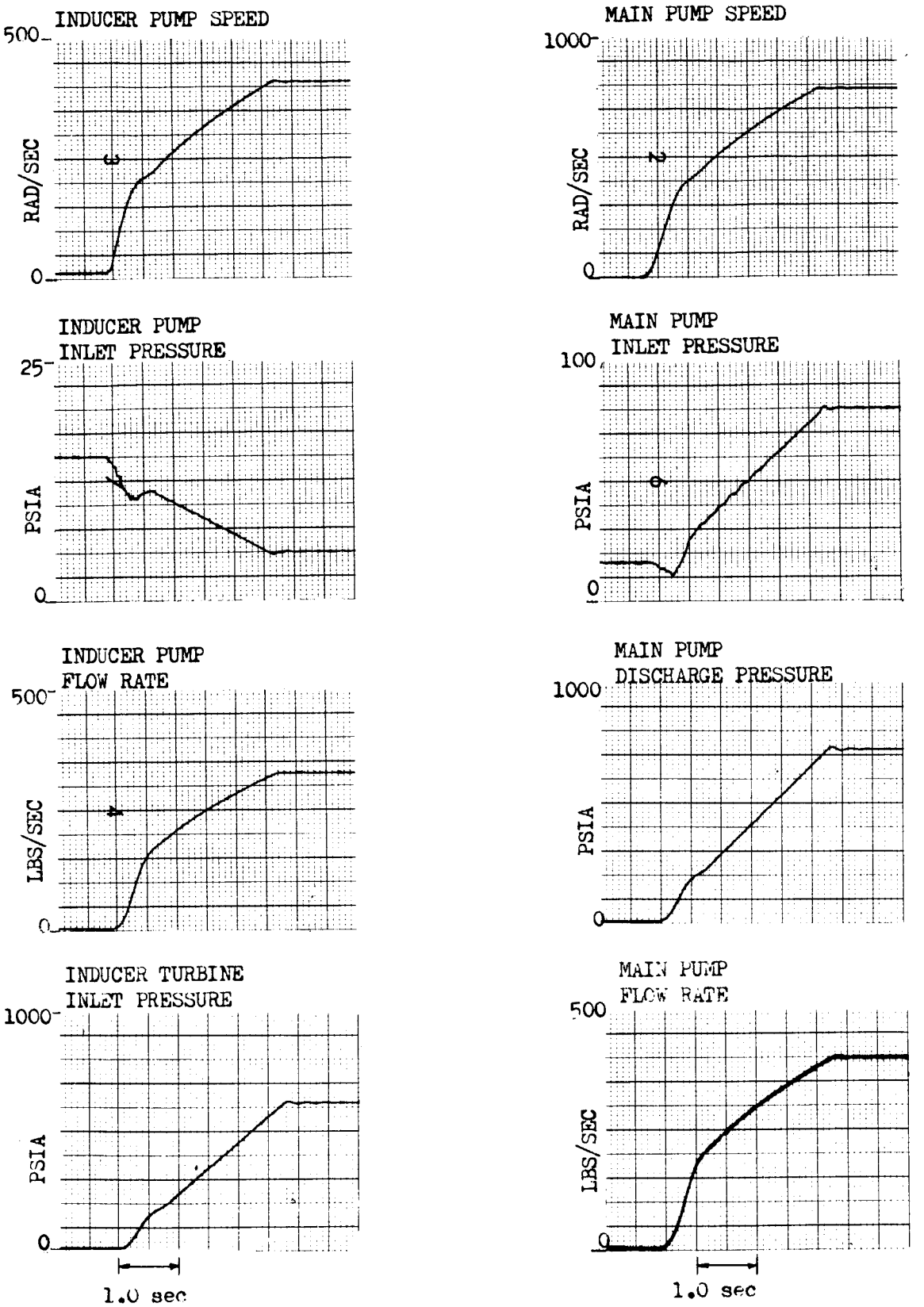


Figure 39. Remote-Coupled Low Moment of Inertia

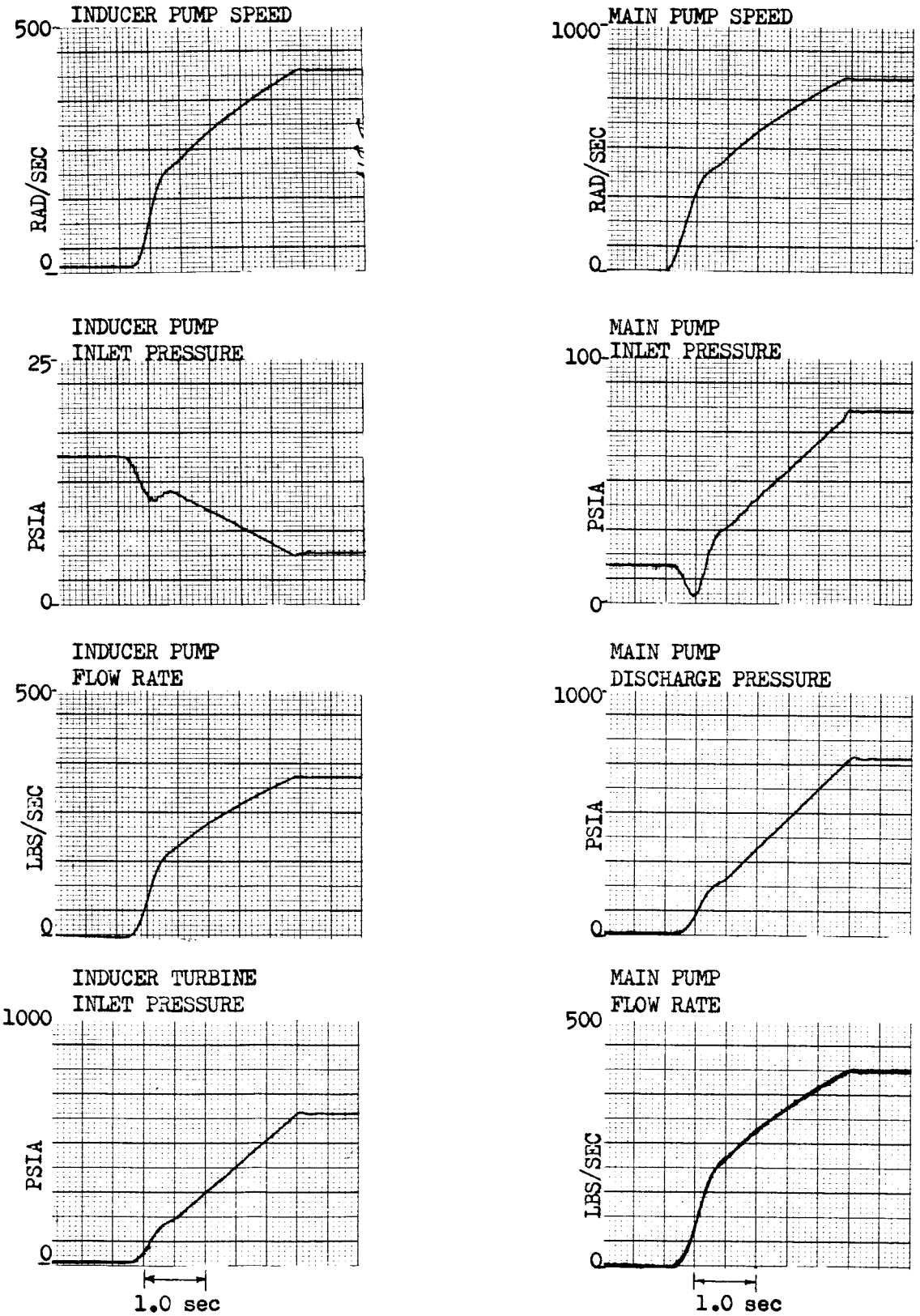


Figure 40. Close-Coupled High Moment of Inertia

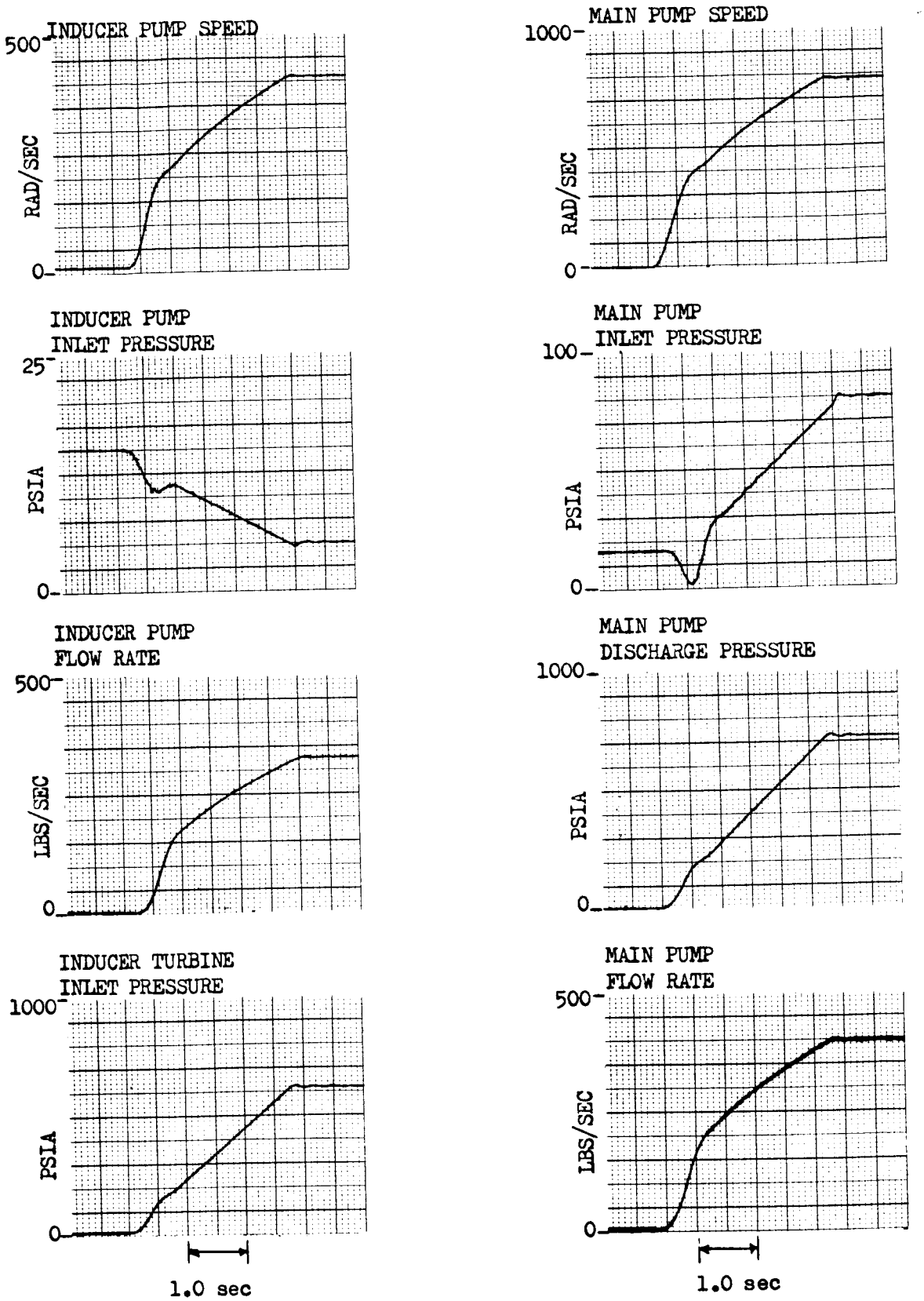


Figure 41. Remote-Coupled High Moment of Inertia

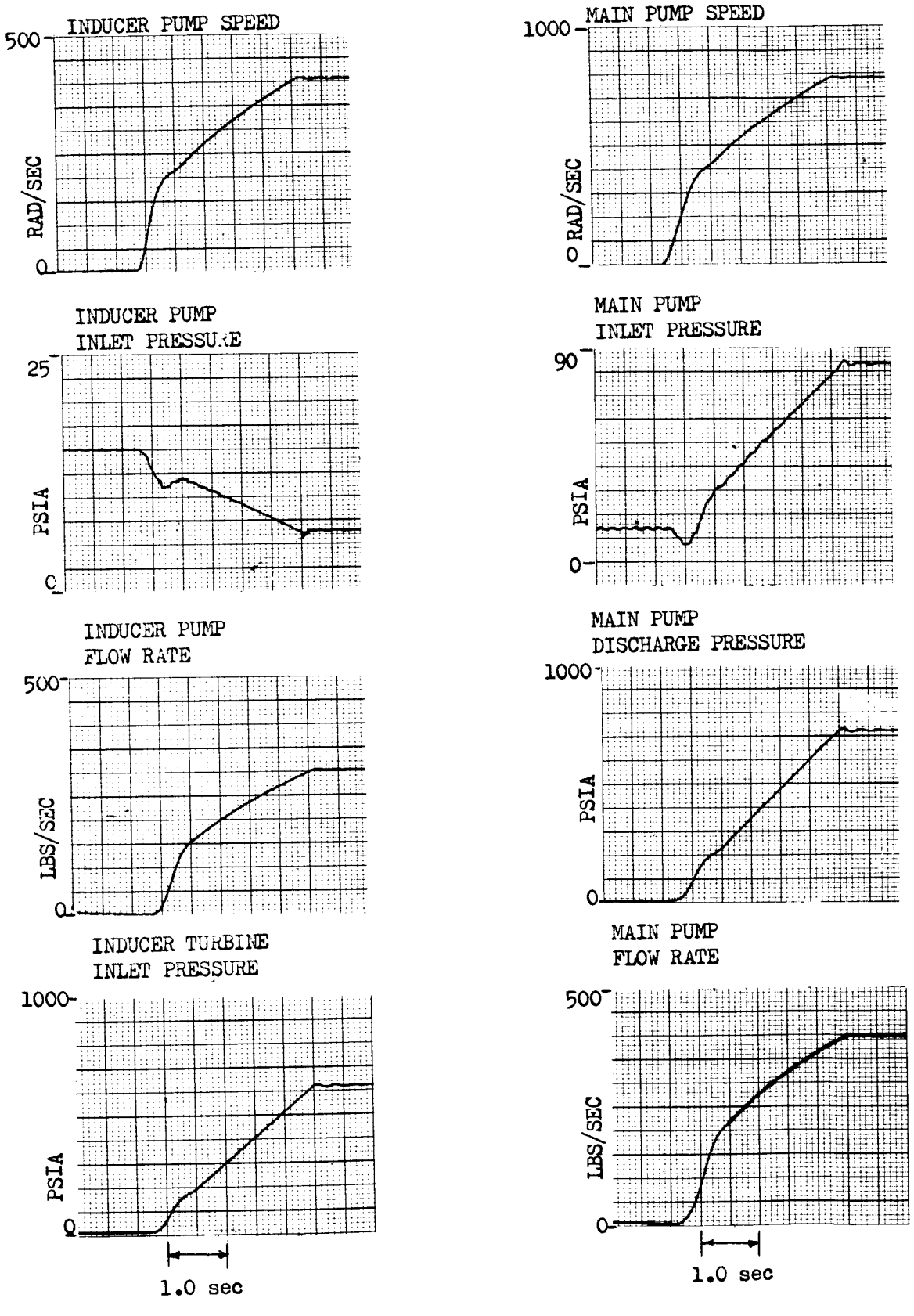


Figure 42. Remote-Coupled Low Coupling Line Fluid Inertia

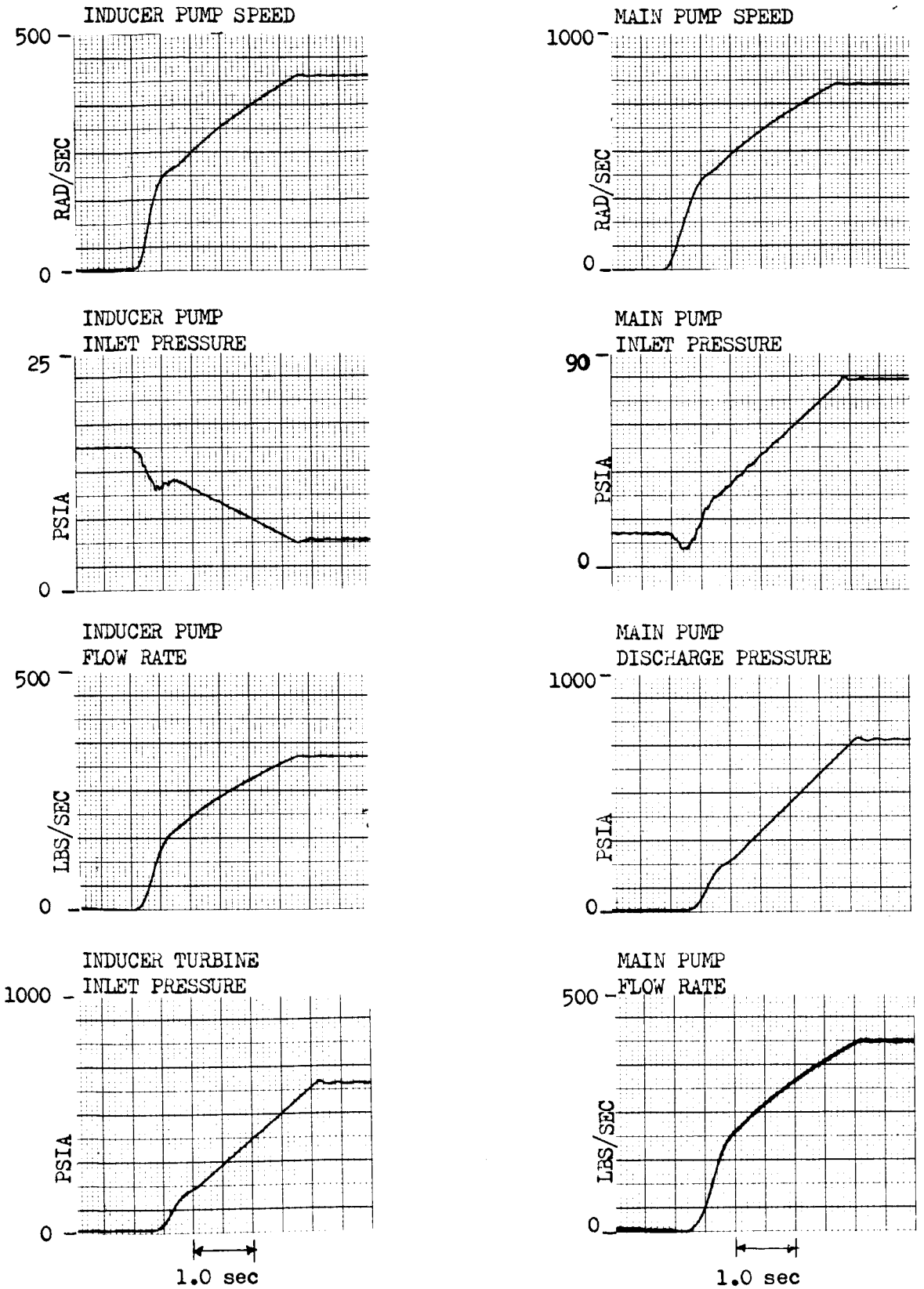


Figure 43. Close-Coupled Low Turbine Feed Line Resistance

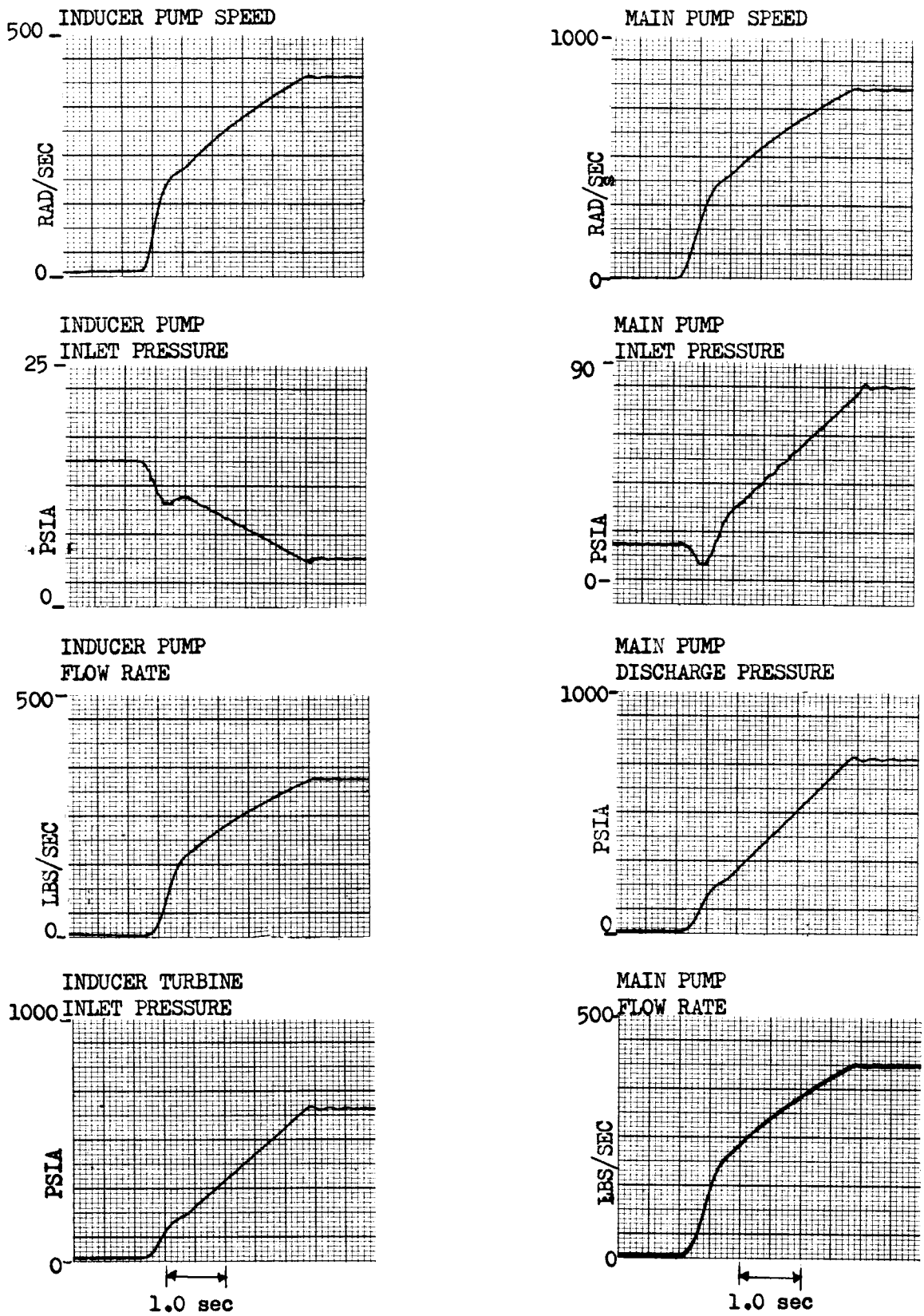


Figure 44. Remote-Coupled Low Turbine Feed Line Resistance

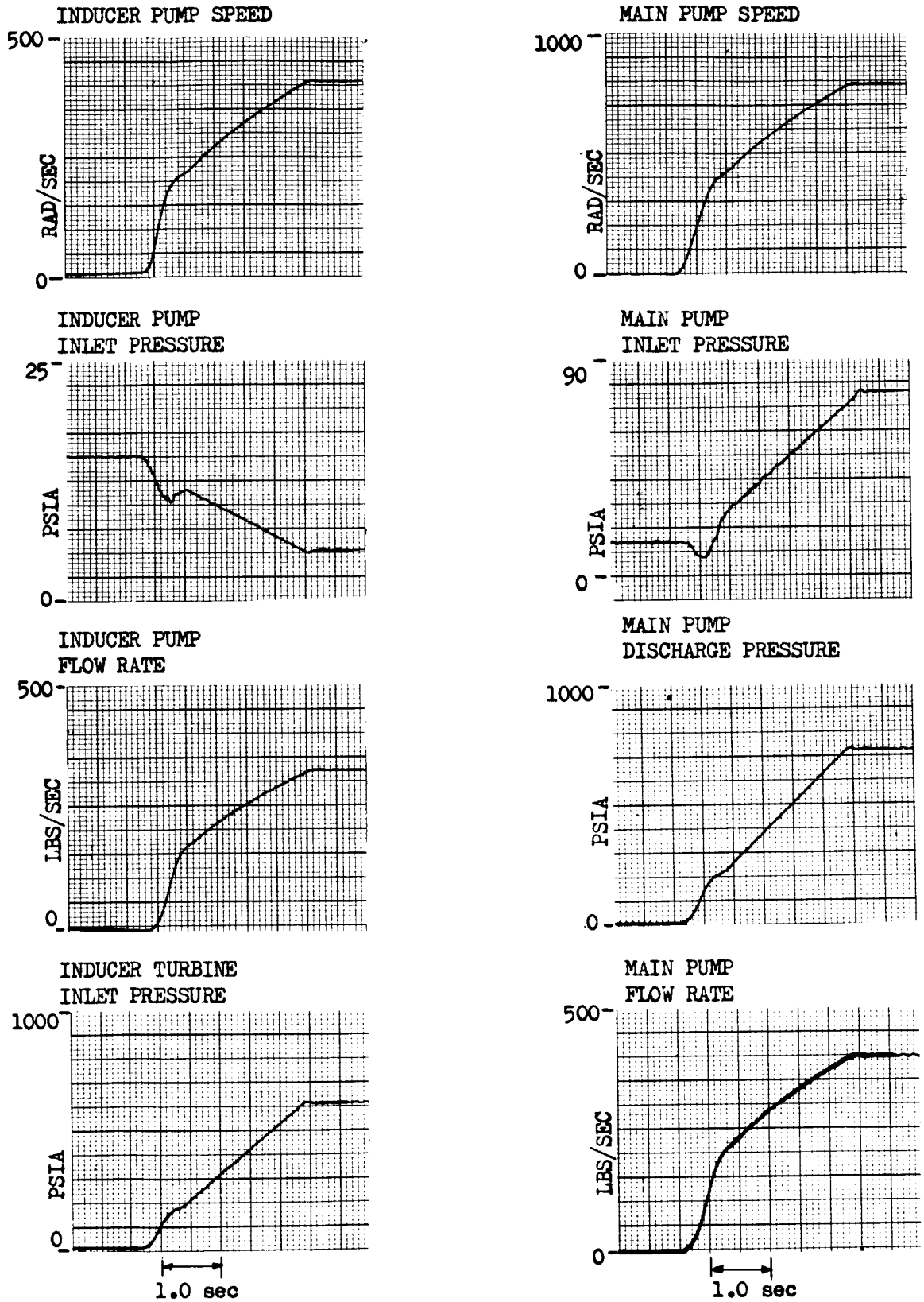


Figure 45. Close-Coupled High Turbine Feed Line Resistance

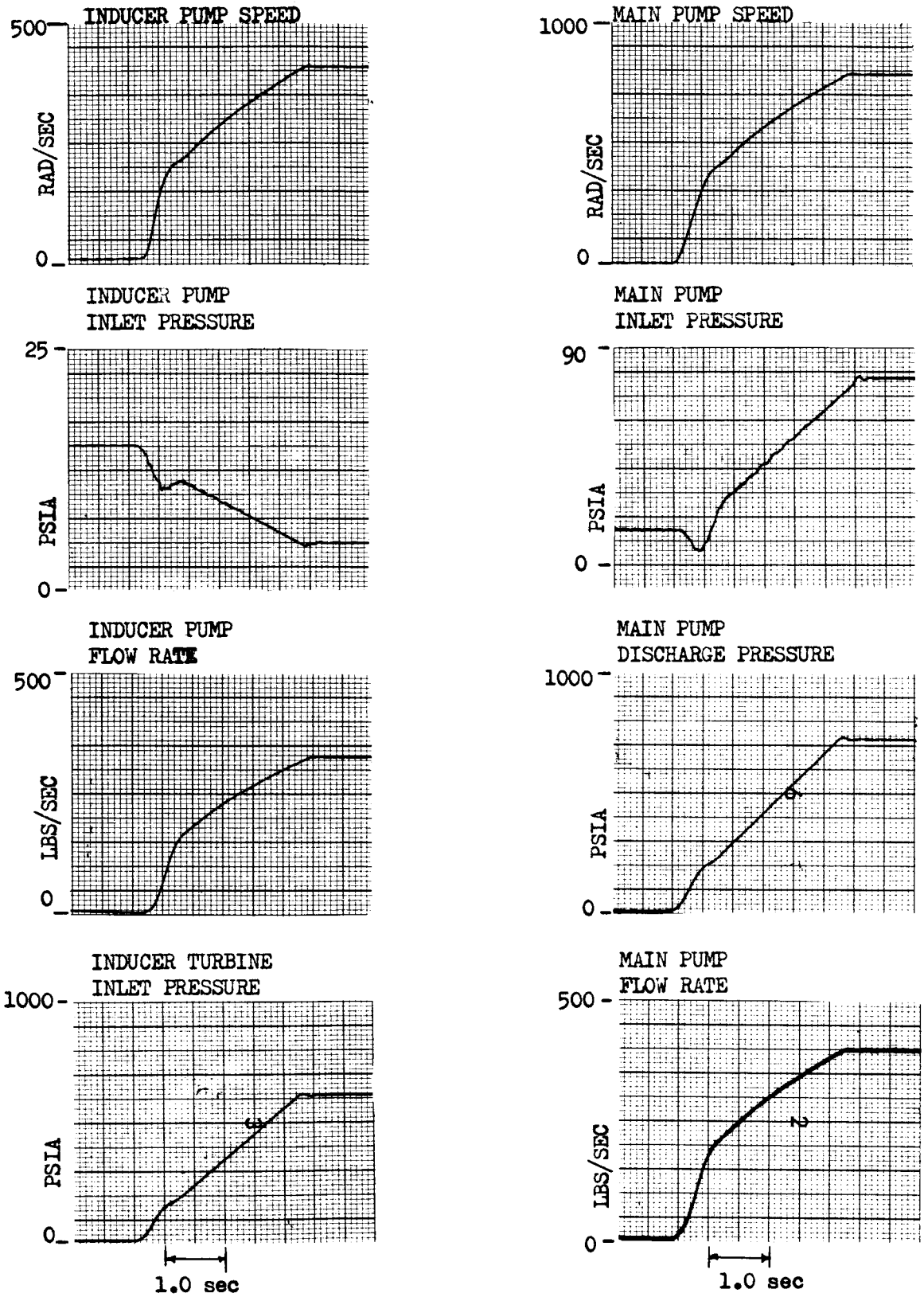


Figure 46. Remote-Coupled High Turbine Feed Line Resistance

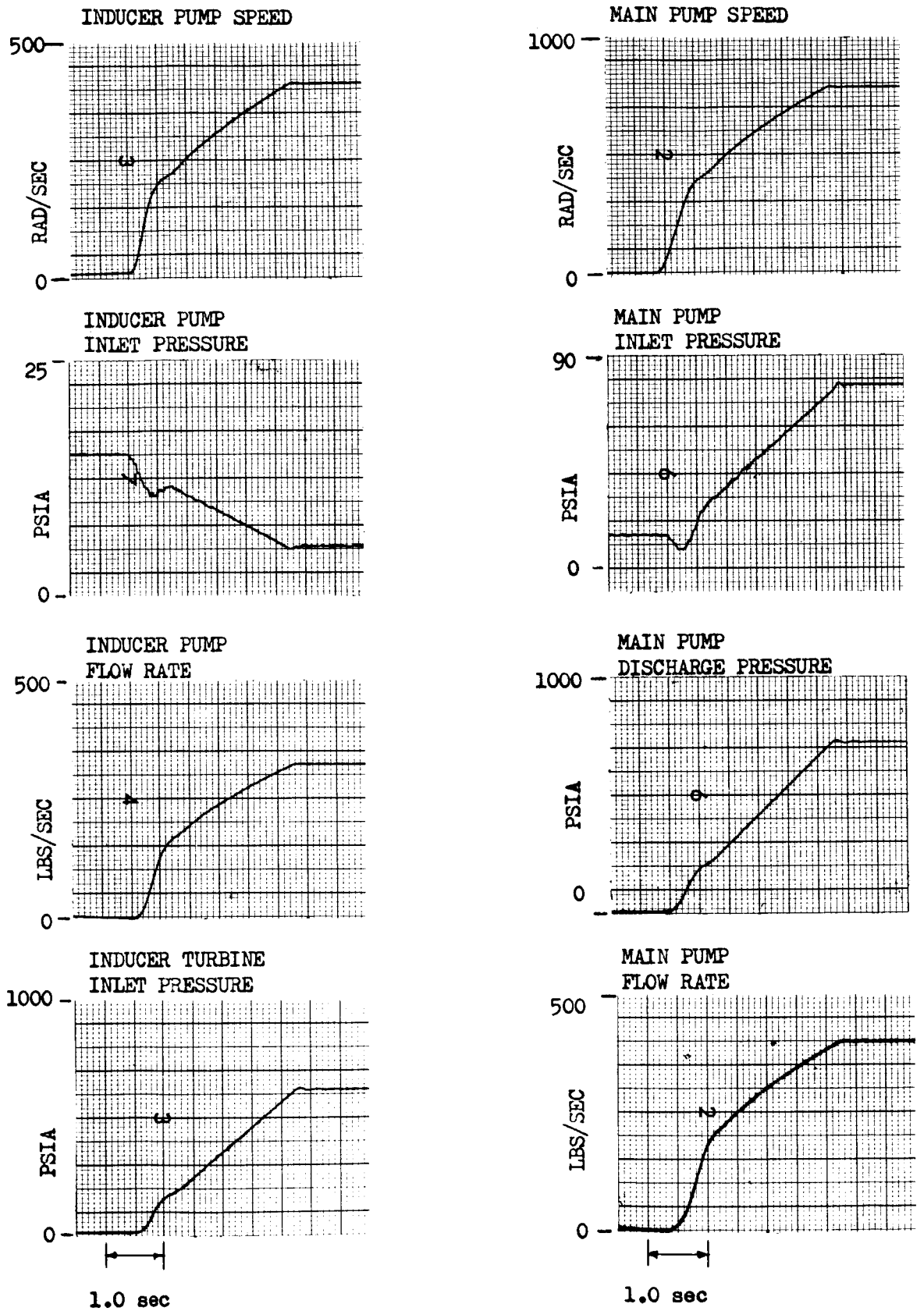


Figure 47. Close-Coupled Low Turbine Feed Line Fluid Inertia

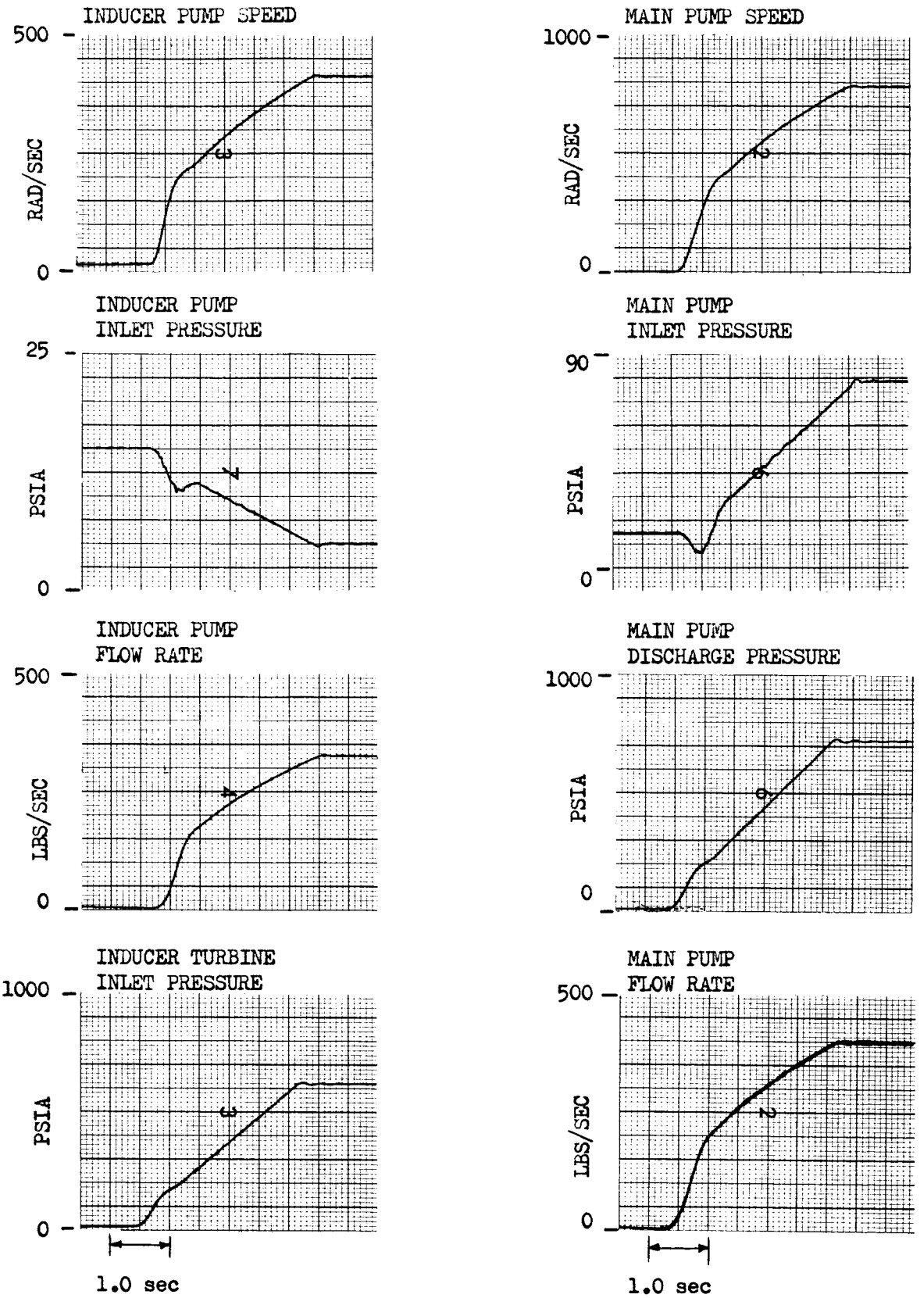


Figure 48. Remote-Coupled Low Turbine Feed Line Fluid Inertia

The final case in this portion of the study involved using the performance curves for a low-head preinducer having a pressure rise of 13 psi compared to about 75 psi for the test preinducer. Use of the low-head preinducer results in less power required to drive the preinducer and a reduction of the turbine flowrate from about 75 lb/sec to 20 lb/sec. This is a distinct advantage in that the main pump flowrate is reduced, resulting in less power required to drive the main pump. The results are presented in Fig. 49 for a close-coupled preinducer mounted in the water test facility with a 3.0-second speed ramp input to the main pump. It was found that the main pump inlet pressure depression is greater because of the reduced preinducer pump head. Slowing down the start, throttling the main flowrate during the first part of the start, or a combination of start time and throttling would improve this situation. It appears, therefore, that a practical low-head preinducer could be adapted to an engine with a possible sacrifice in start time.

TEST SYSTEM PERFORMANCE

The system performance of the proposed water test series was analyzed for both a close- and remote-coupled preinducer. For this study, the main pump drive was represented by a linear speed ramp input rather than a torque input, which results in less-severe system dynamic effects. With a torque input, the initial speed acceleration is high because of the low required pump torque at low speed and the relatively high input torque available from the drive motor. The resulting high pump acceleration produces more dynamic effects and a larger dip in the pump inlet pressure. For example, a 1.5-second speed ramp start results in less main pump inlet pressure loss than a 3.0-second torque input.

The test conditions for which predictions were made are presented in Table 3, and the results shown in Fig. 50 through 82. Smooth starts and speed changes were achieved for all ramp conditions with negligible dynamics. These results indicate that the inducer, as designed, will perform satisfactorily during transients in the range of engine start and throttling times.

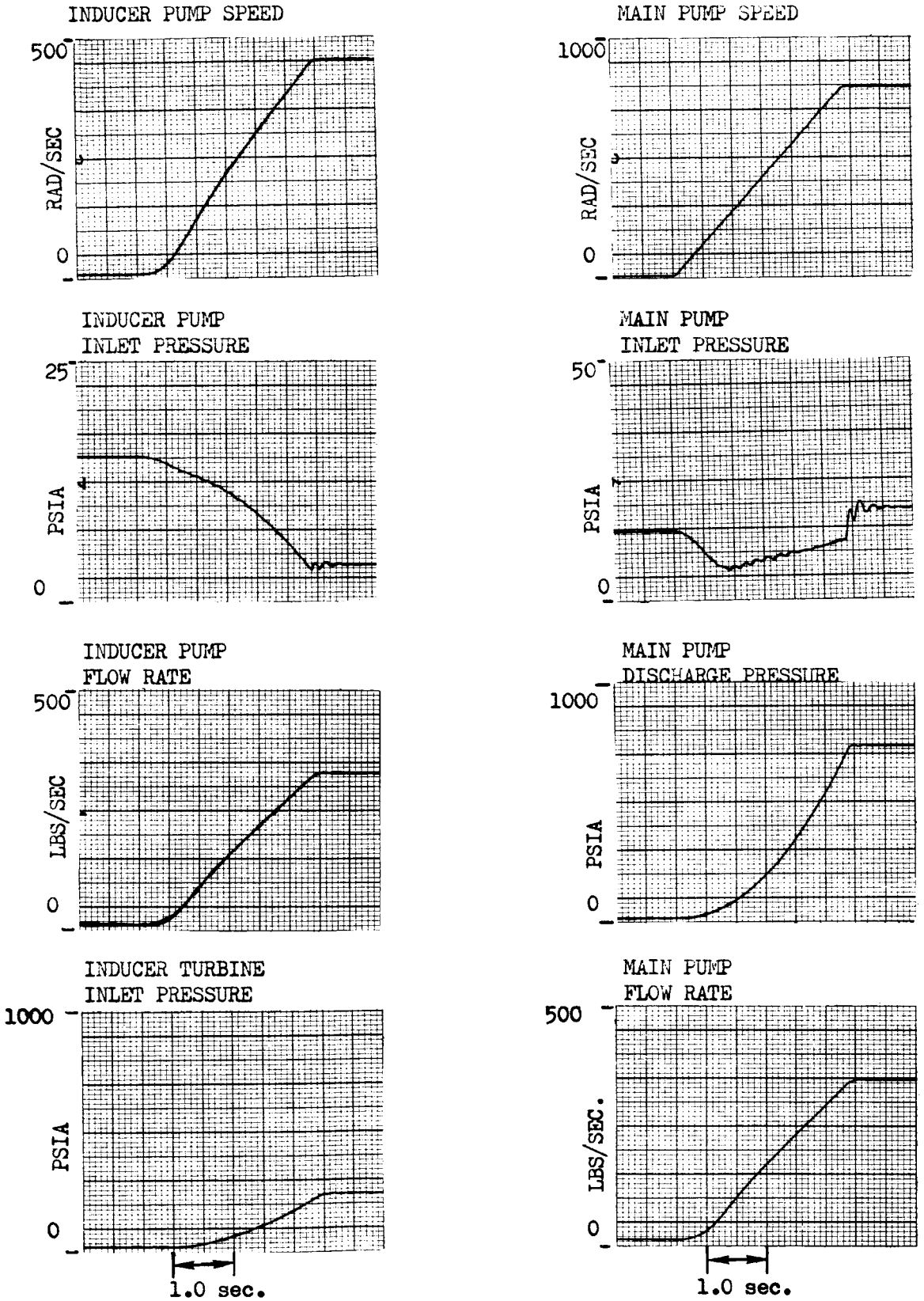


Figure 49. Close-Coupled Low-Head Inducer

TABLE 3

TRANSIENT TEST CONDITIONS*

1. Accelerate from 0- to 100-percent N and 100-percent Q/N in:	1.5	2.0	2.5	3.0	4.0
2. Accelerate from 0- to 100-percent N and 120-percent Q/N in:	2.0	3.0	4.0	--	--
3. Ramp from 100-percent N, 100-percent Q/N to 65-percent N in:	1.0	2.0	3.0	4.0	3.0
Accelerate from 65-percent N to 100-percent N in:	0.5	1.0	1.5	2.0	4.0

*Values are in seconds

N = speed

Q = flow

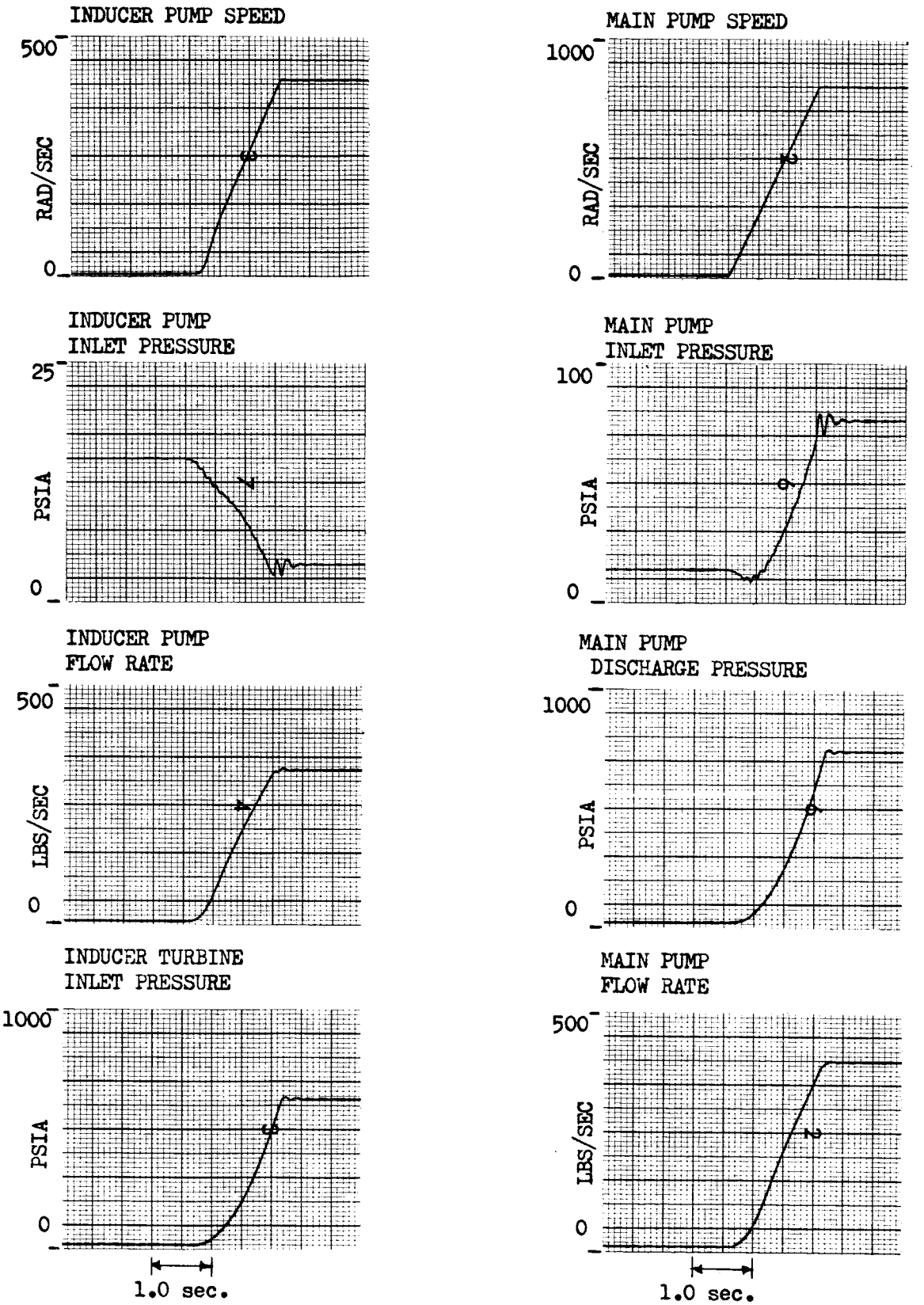


Figure 50. Close-Coupled Test Start to 100-Percent Q/N, 1.5-Second Speed Ramp

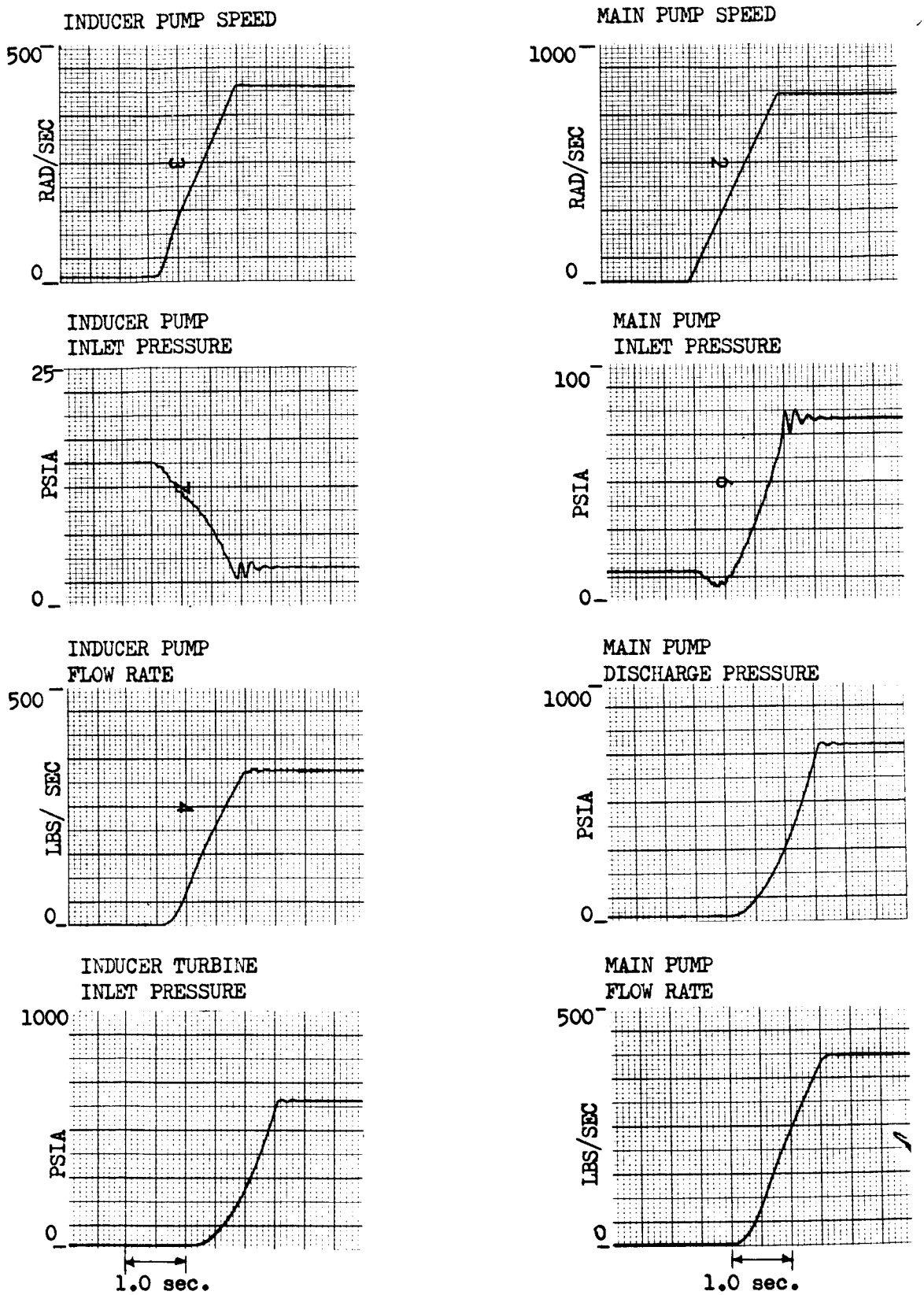


Figure 51. Remote-Coupled Test Start to 100-Percent Q/N, 1.5-Second Speed Ramp

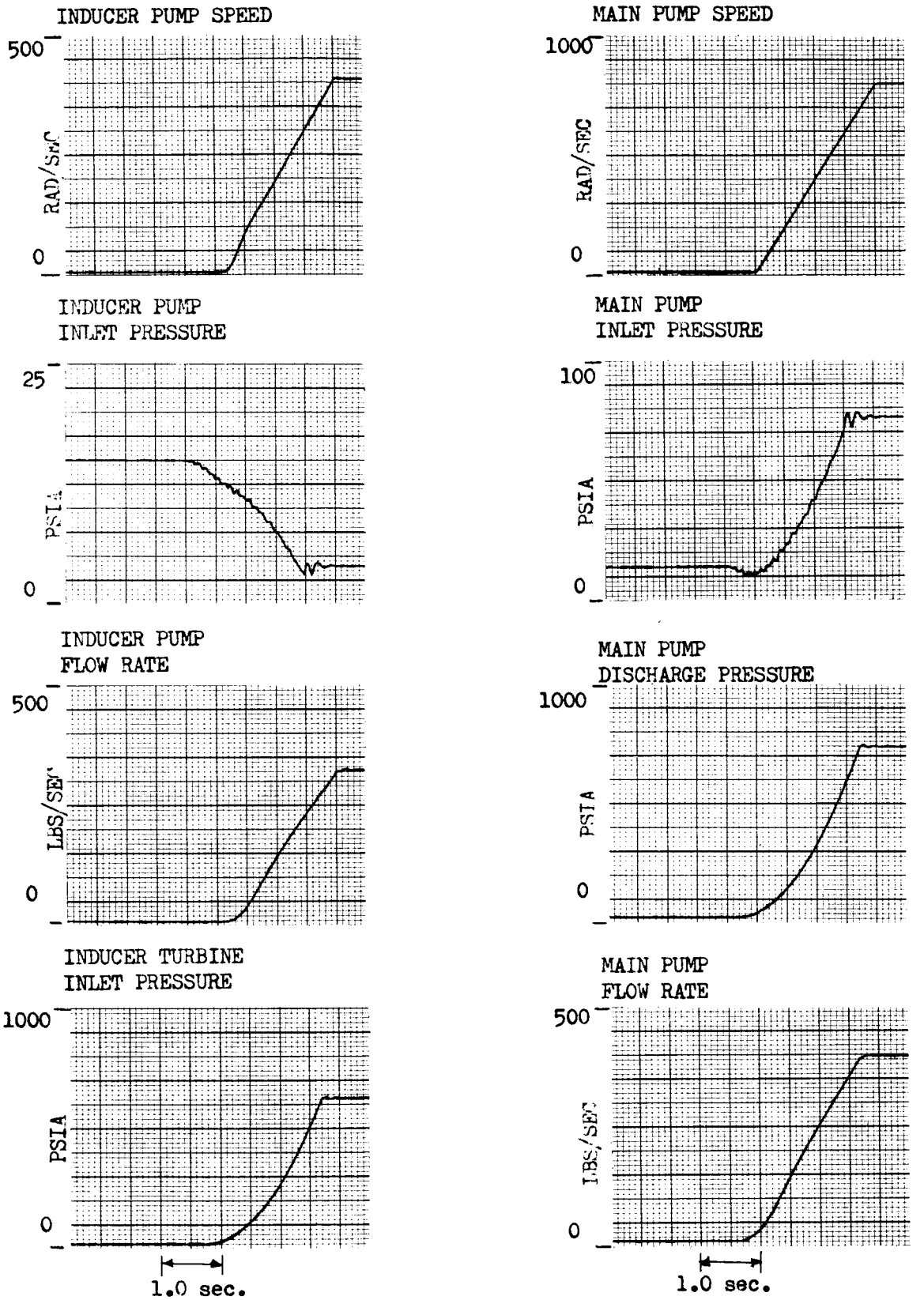


Figure 52. Close-Coupled Test Start to 100-Percent Q/N, 2.0-Second Speed Ramp

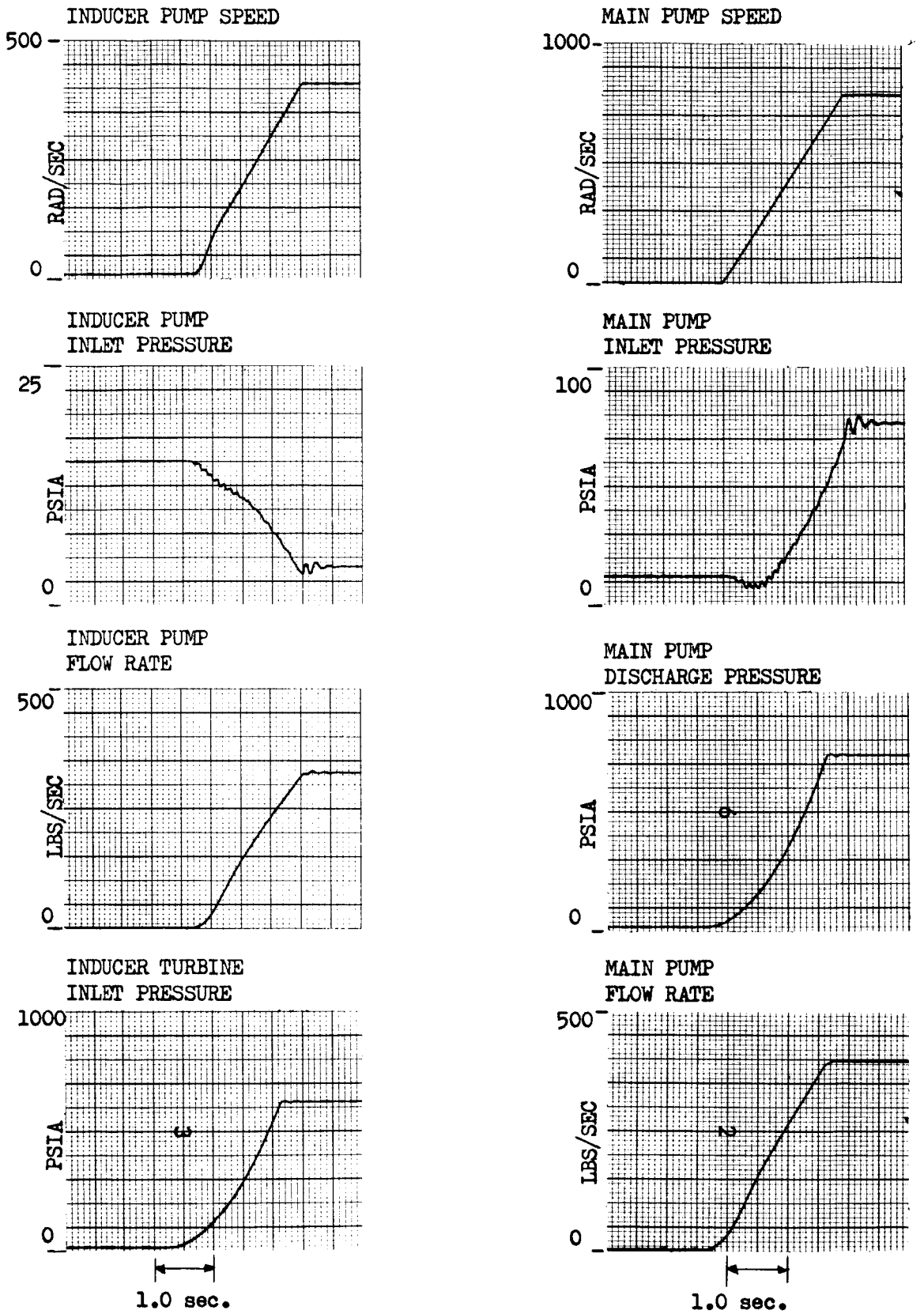


Figure 53. Remote-Coupled Test Start to 100-Percent Q/N, 2.0-Second Speed Ramp

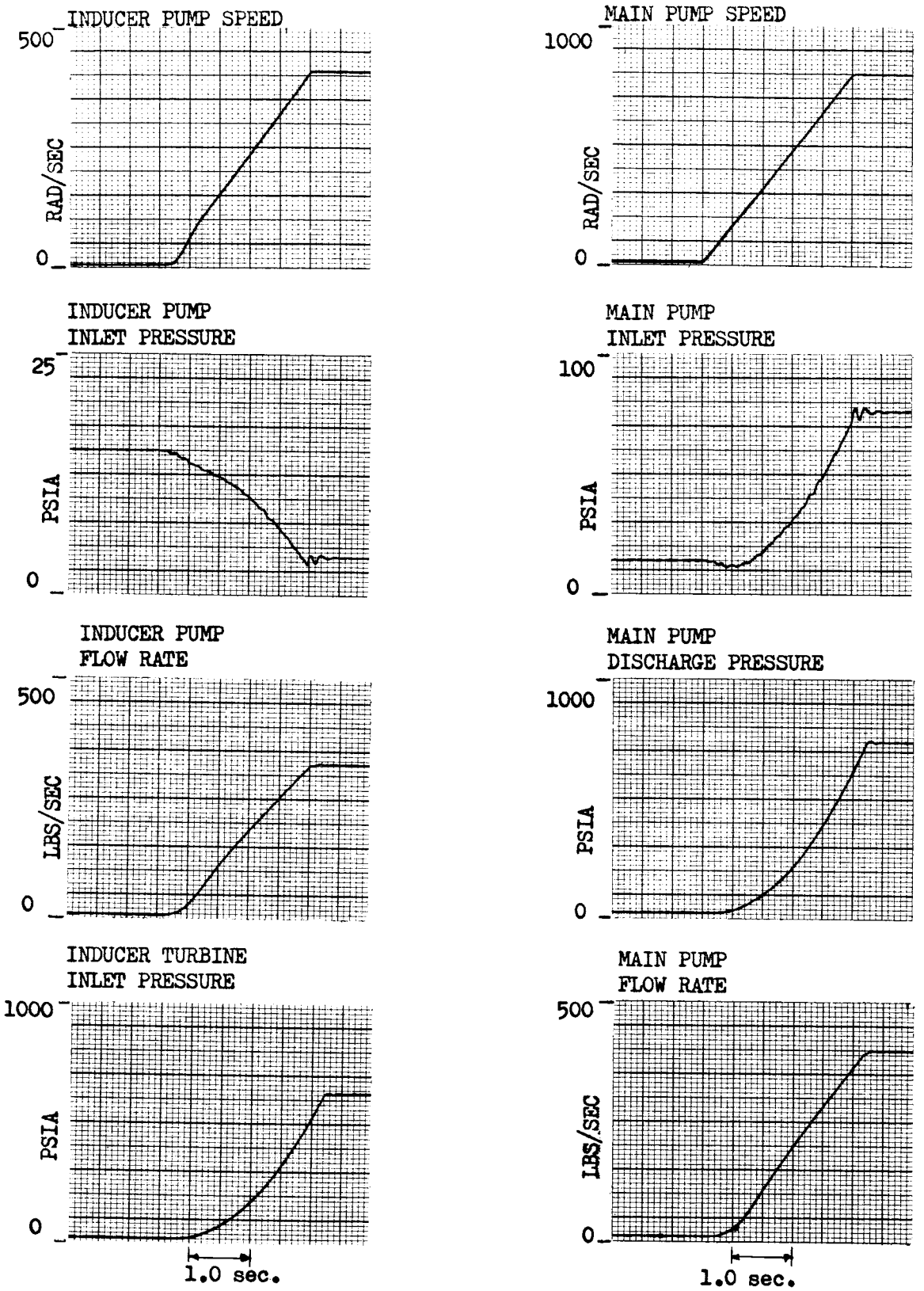


Figure 54. Close-Coupled Test Start to 100-Percent Q/N, 2.5-Second Speed Ramp

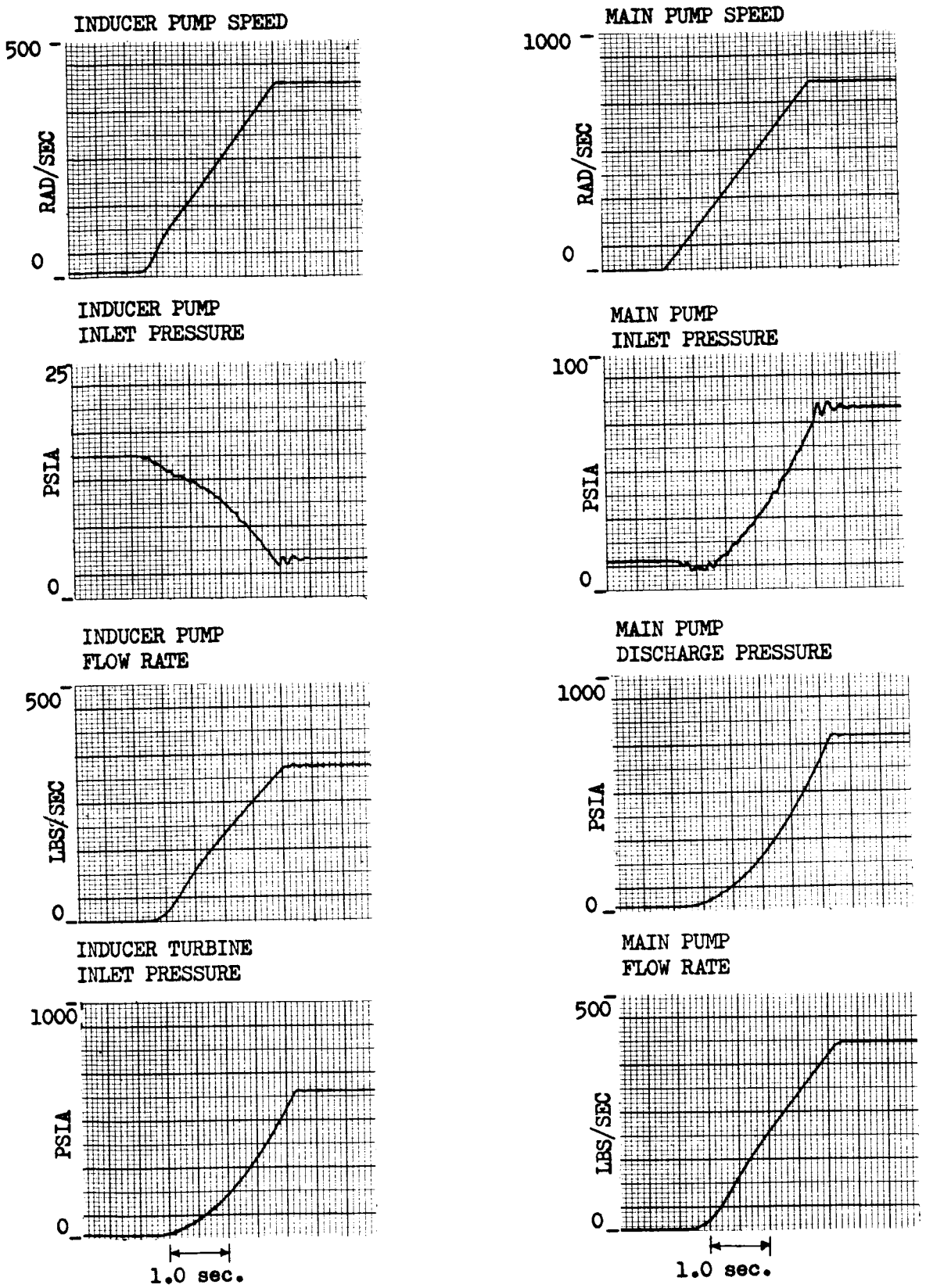


Figure 55. Remote-Coupled Test Start to 100-Percent Q/N, 2.5-Second Speed Ramp

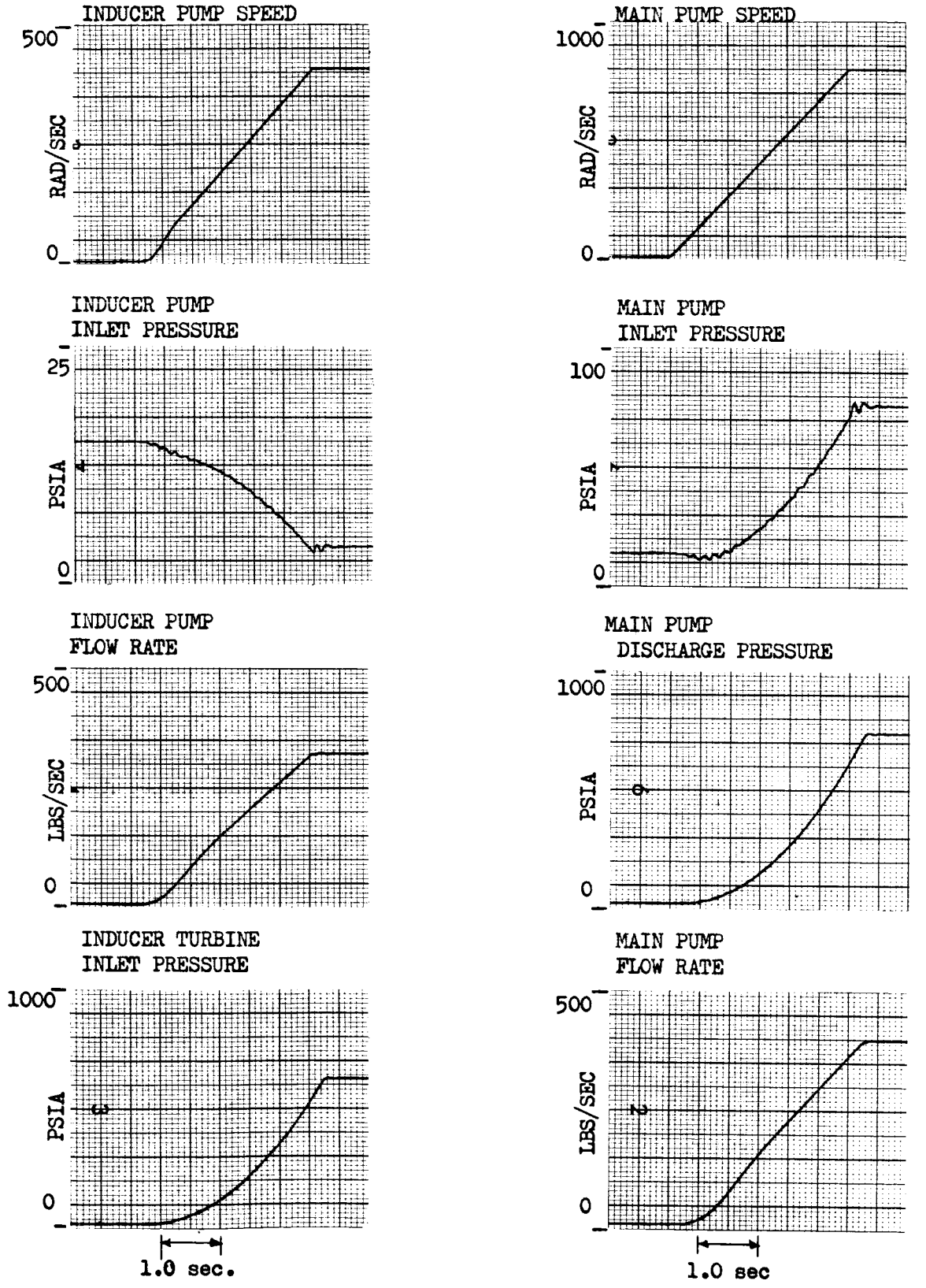


Figure 56. Close-Coupled Test Start to 100-Percent Q/N, 3.0-Second Speed Ramp

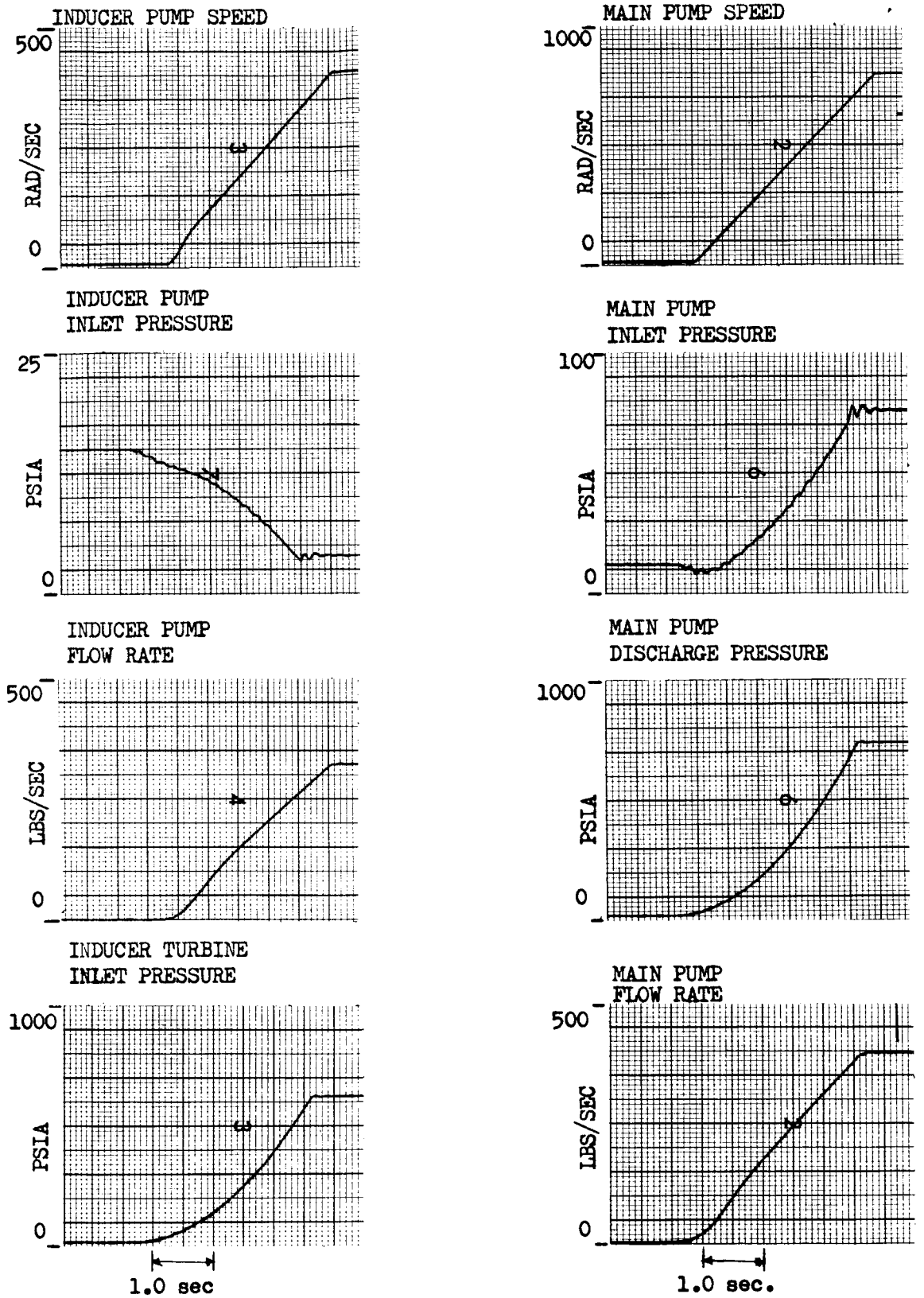


Figure 57. Remote-Coupled Test Start to 100-Percent Q/N, 3.0-Second Speed Ramp

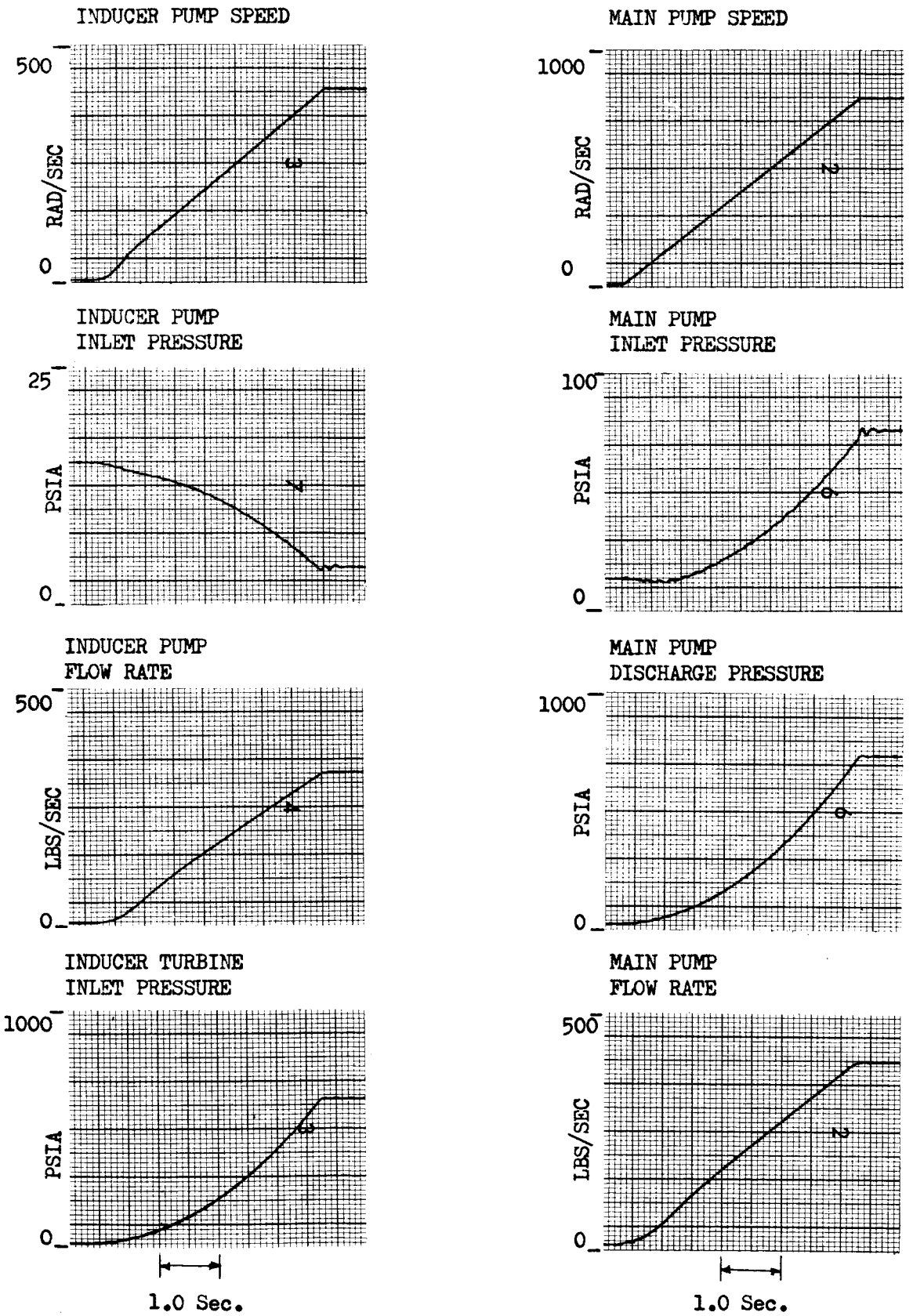


Figure 58. Close-Coupled Test Start to 100-Percent Q/N, 4.0-Second Speed Ramp

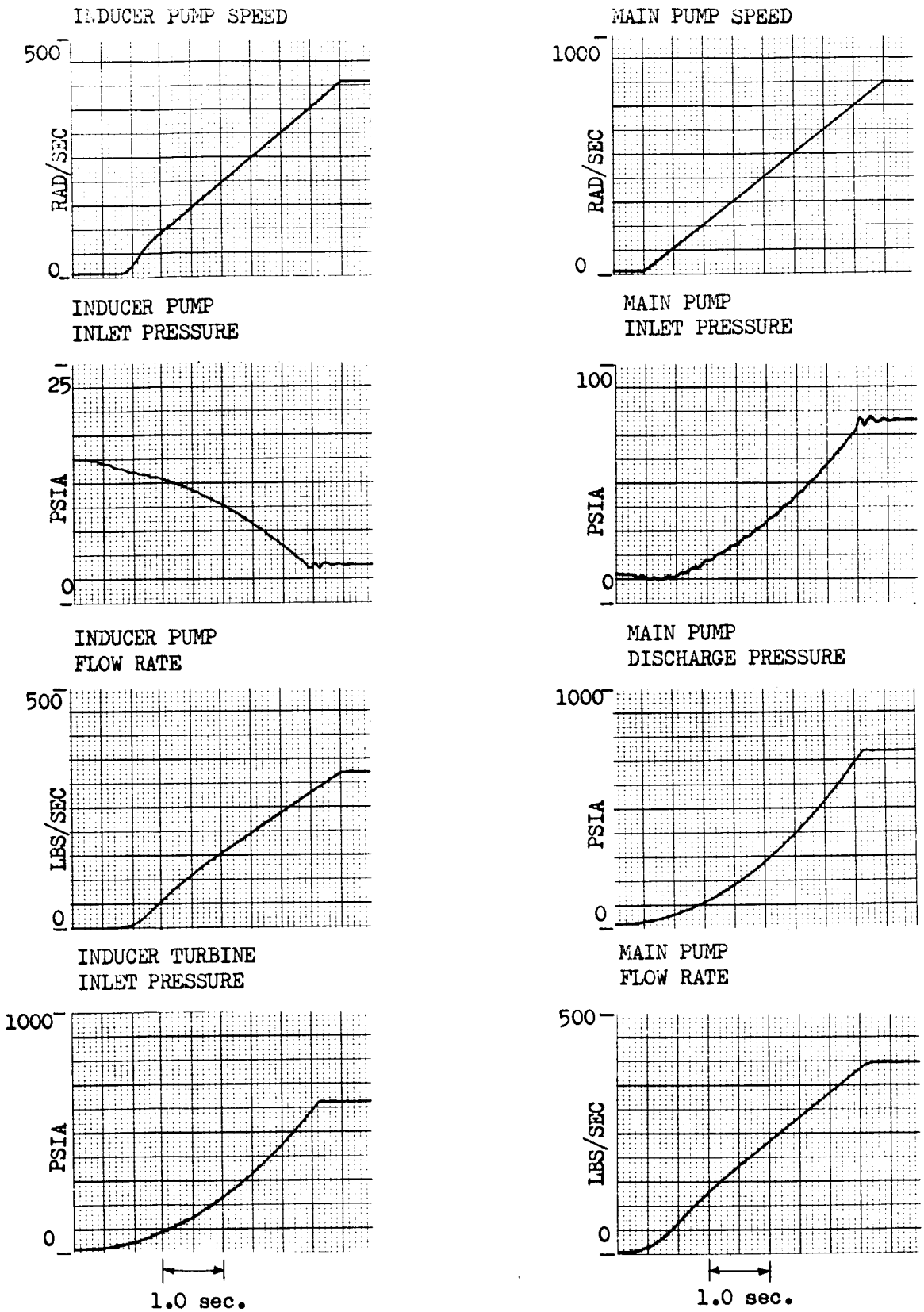


Figure 59. Remote-Coupled Test Start to 100-Percent Q/N, 4.0-Second Speed Ramp

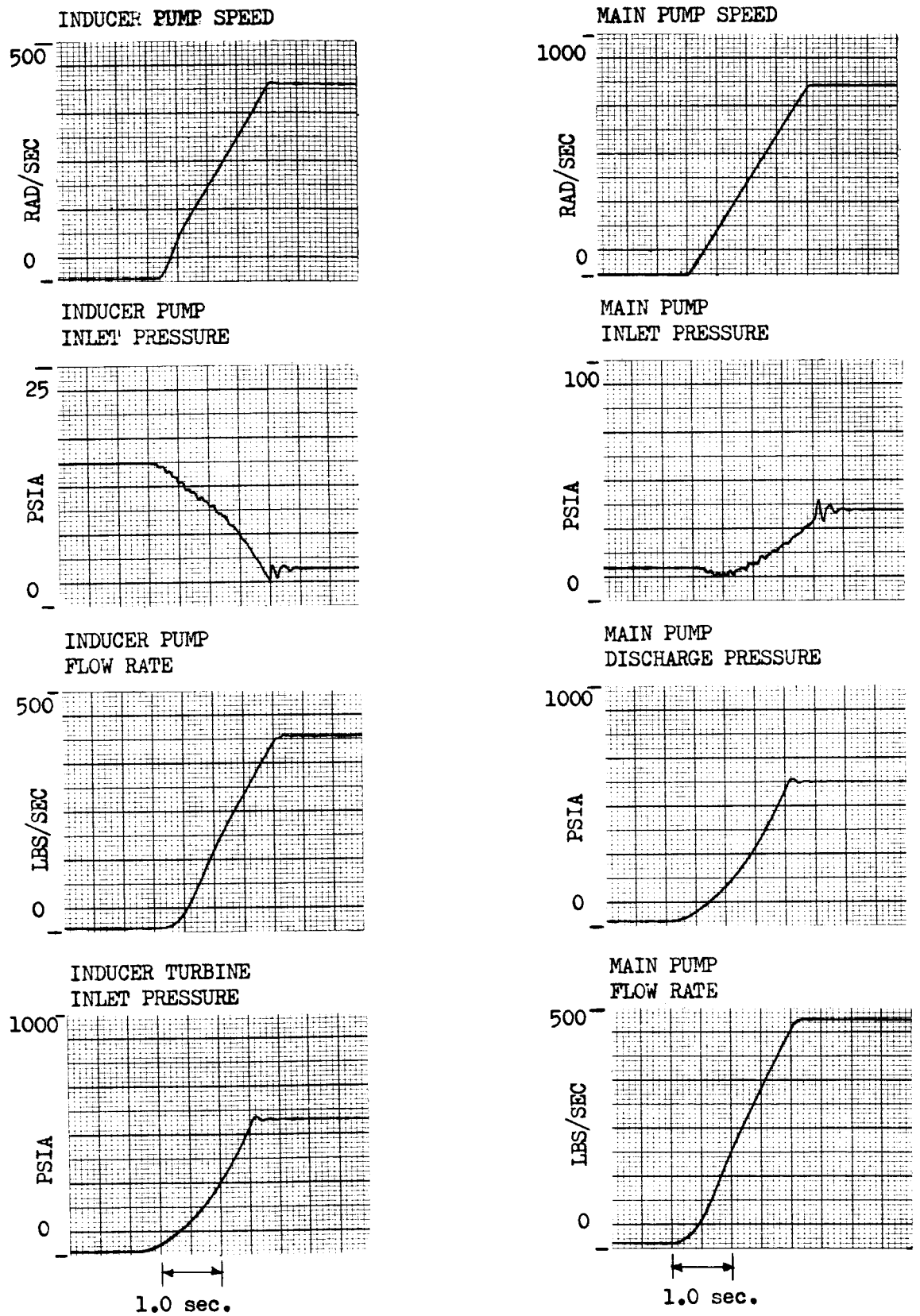


Figure 60. Close-Coupled Test Start to 120-Percent Q/N, 2.0-Second Speed Ramp

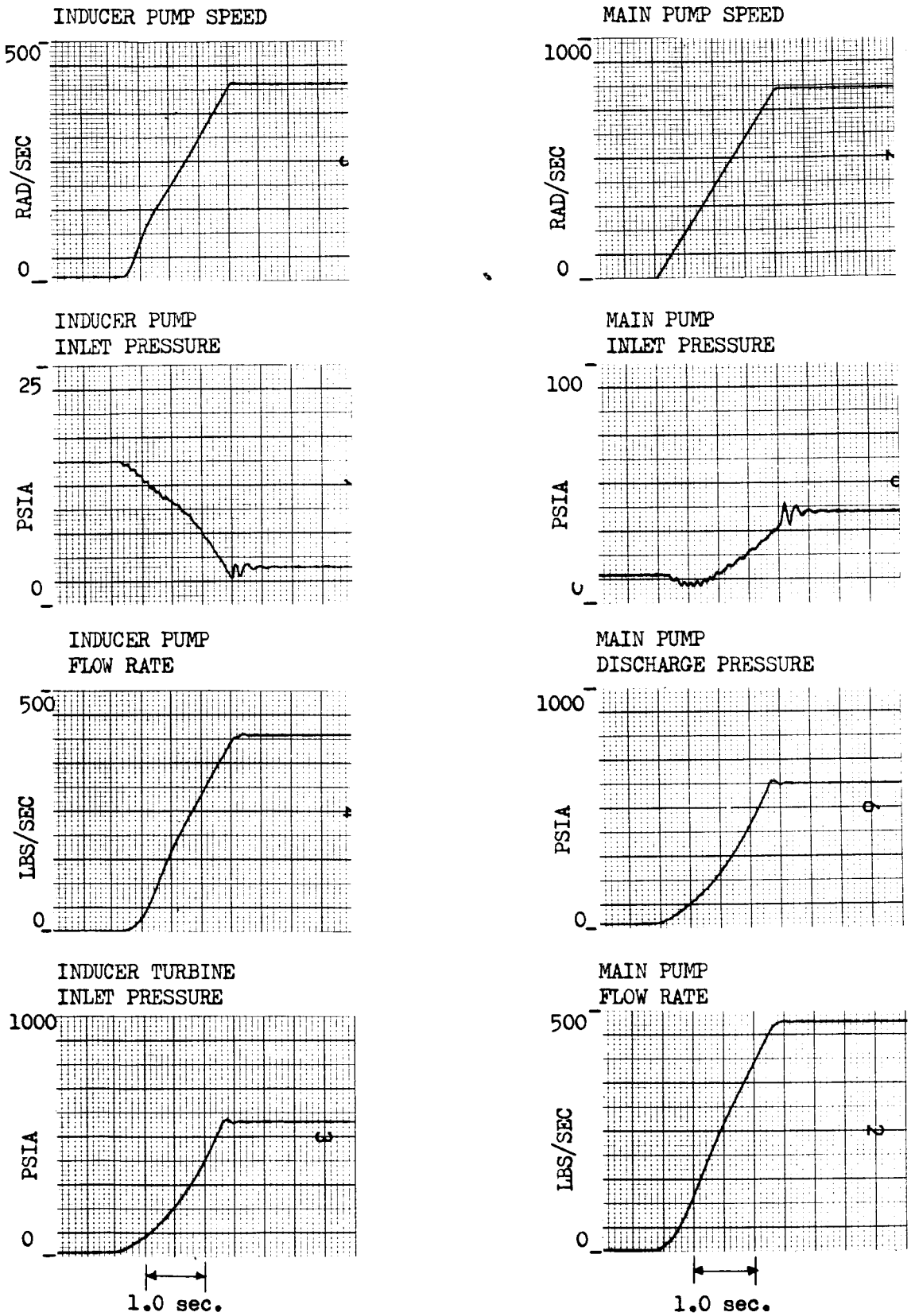


Figure 61. Remote-Coupled Test Start to 120-Percent Q/N, 2.0-Second Speed Ramp

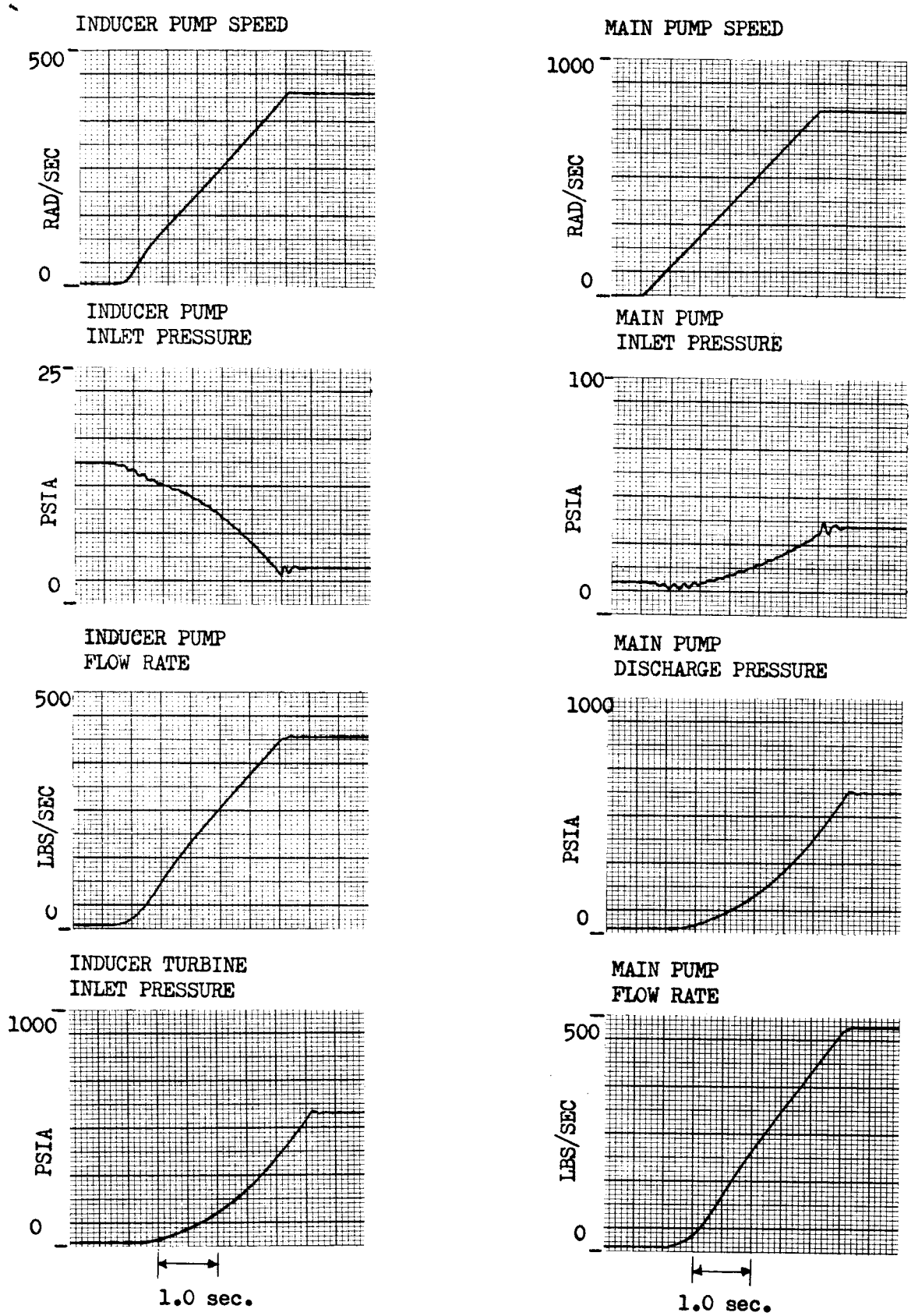


Figure 62. Close-Coupled Test Start to 120-Percent Q/N, 3.0-Second Speed Ramp

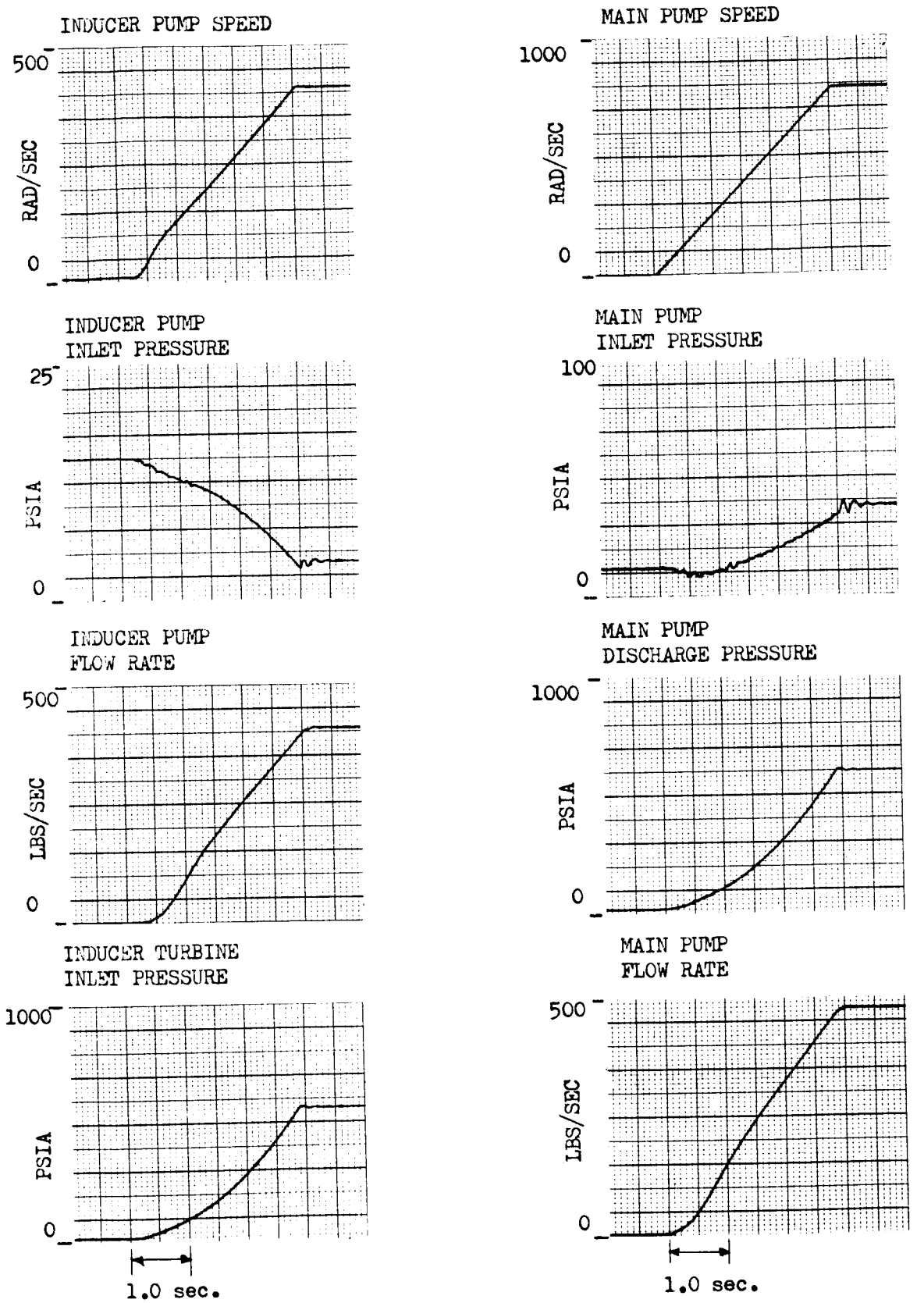


Figure 63. Remote-Coupled Test Start to 120-Percent Q/N, 3.0-Second Speed Ramp

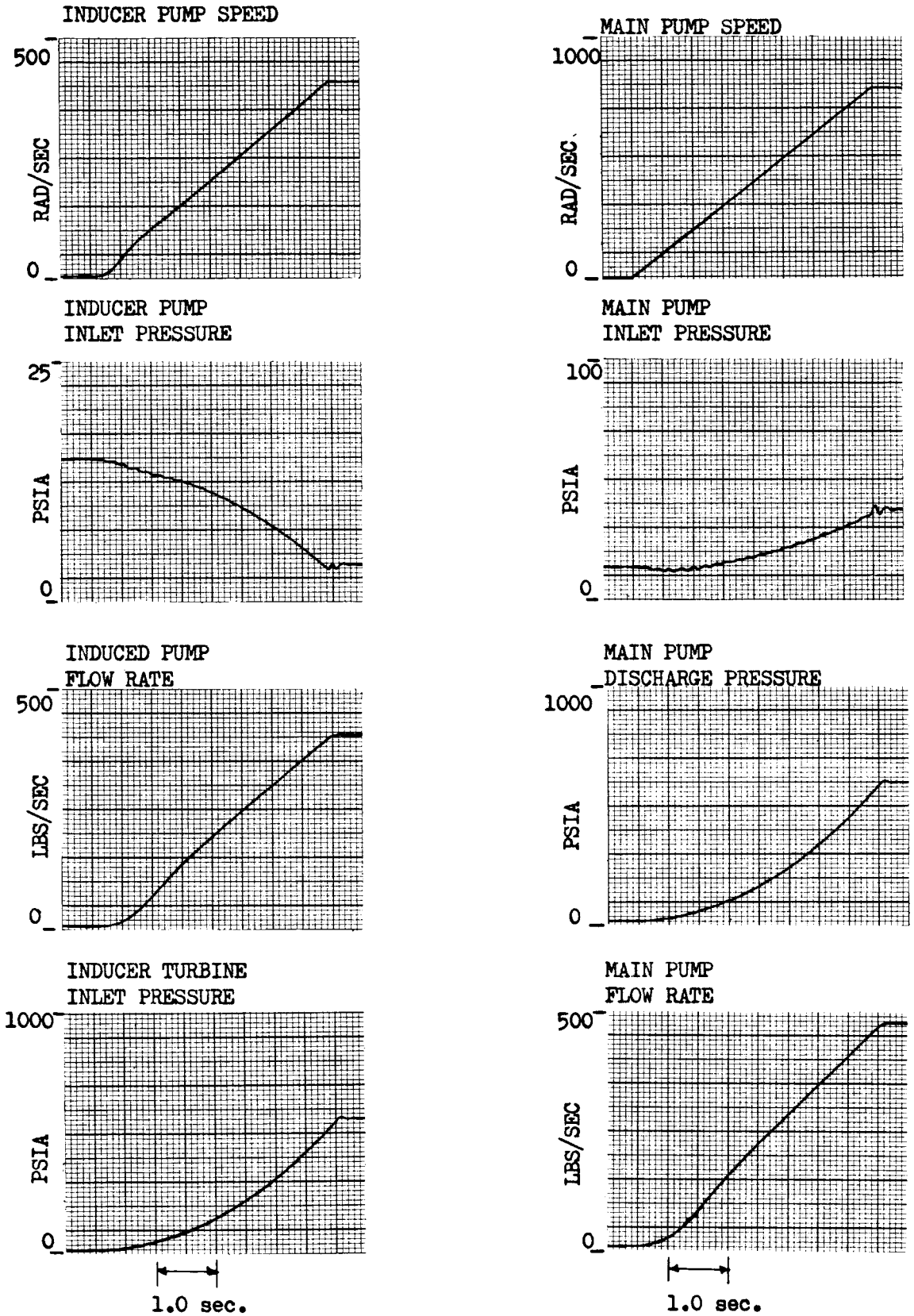


Figure 64. Close-Coupled Test Start to 120-Percent Q/N, 4.0-Second Speed Ramp

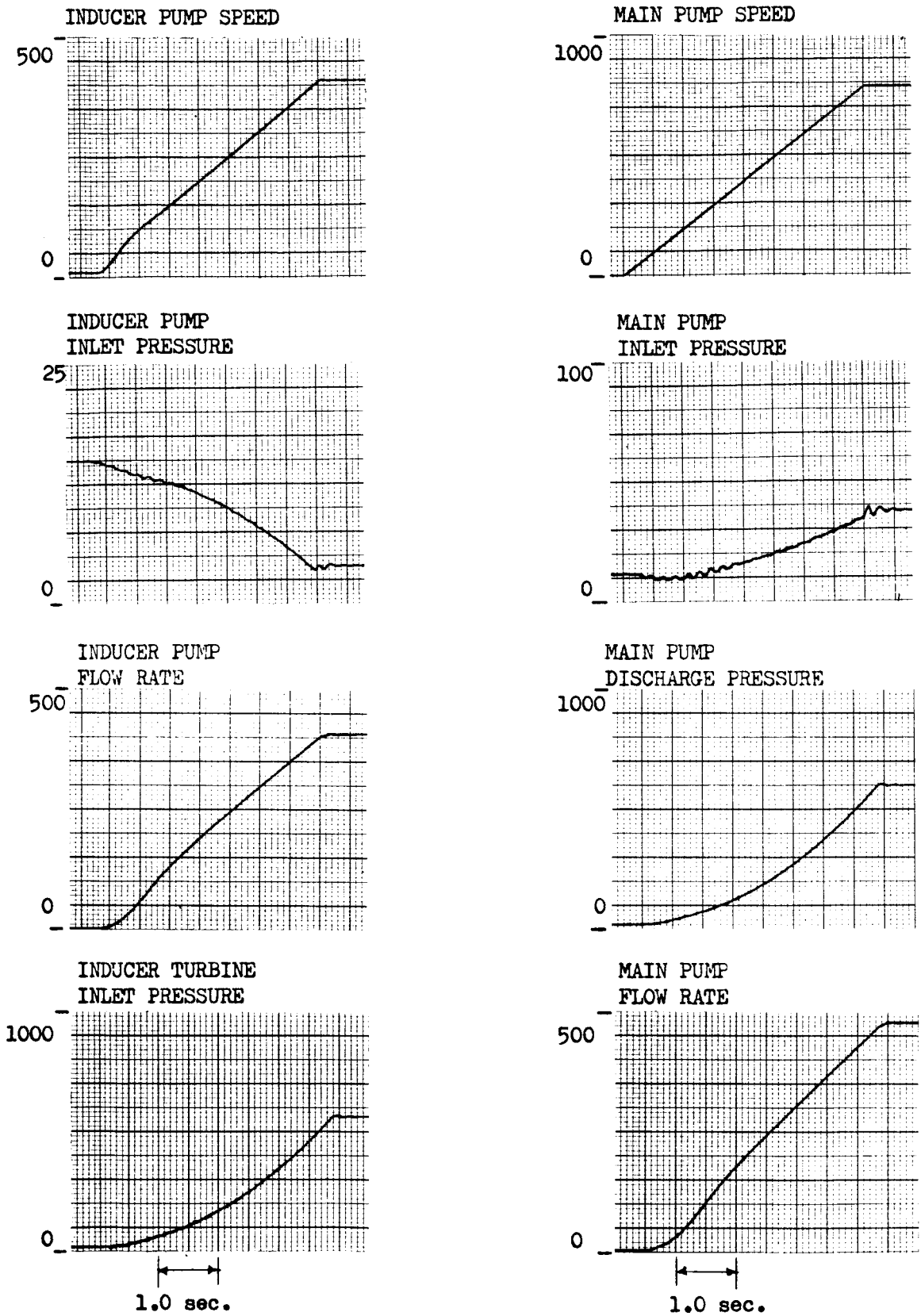


Figure 65. Remote-Coupled Test Start to 120-Percent Q/N, 4.0-Second Speed Ramp

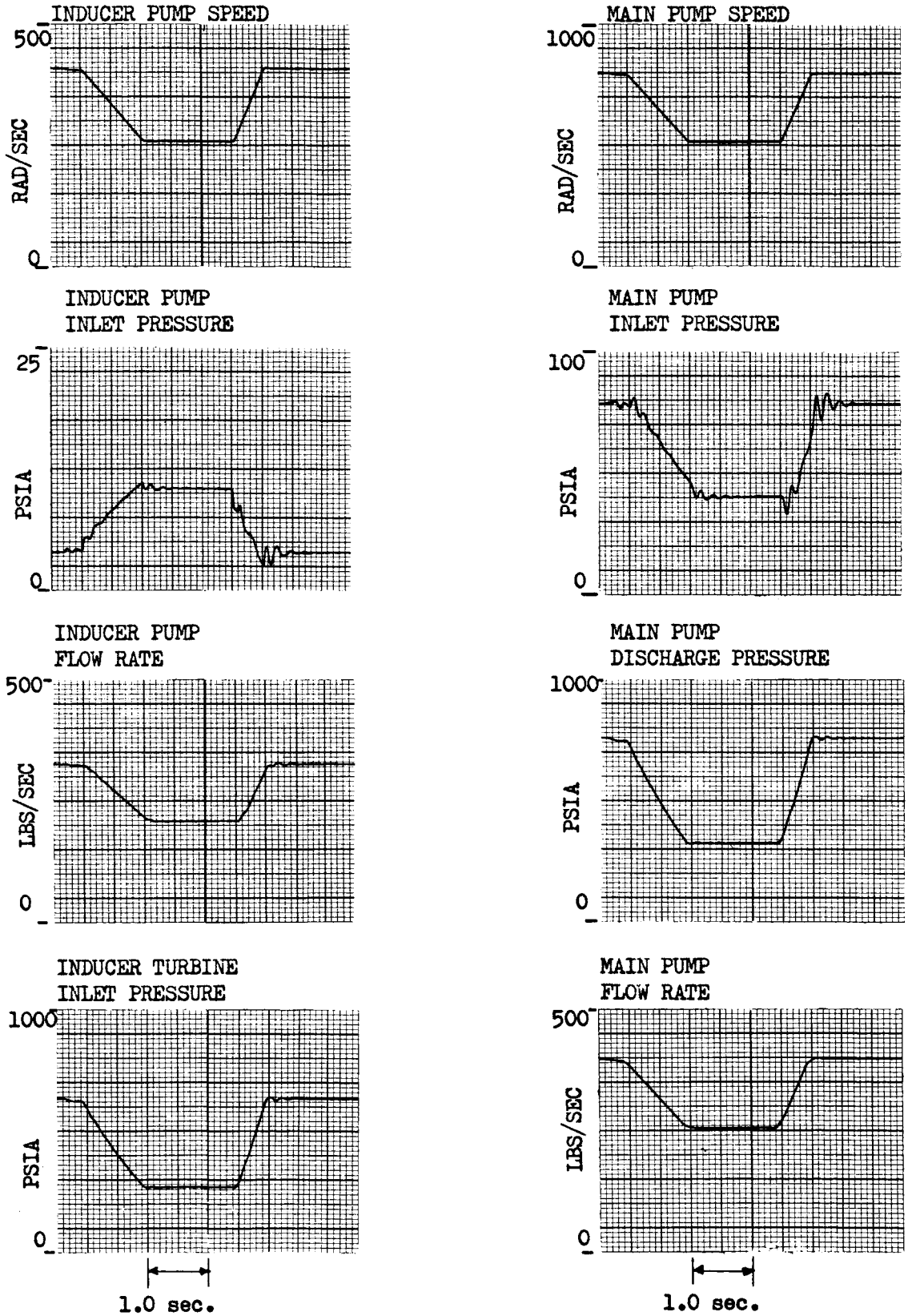


Figure 66. Remote-Coupled Test Throttling, 1.0-Second Deceleration, 0.5-Second Acceleration

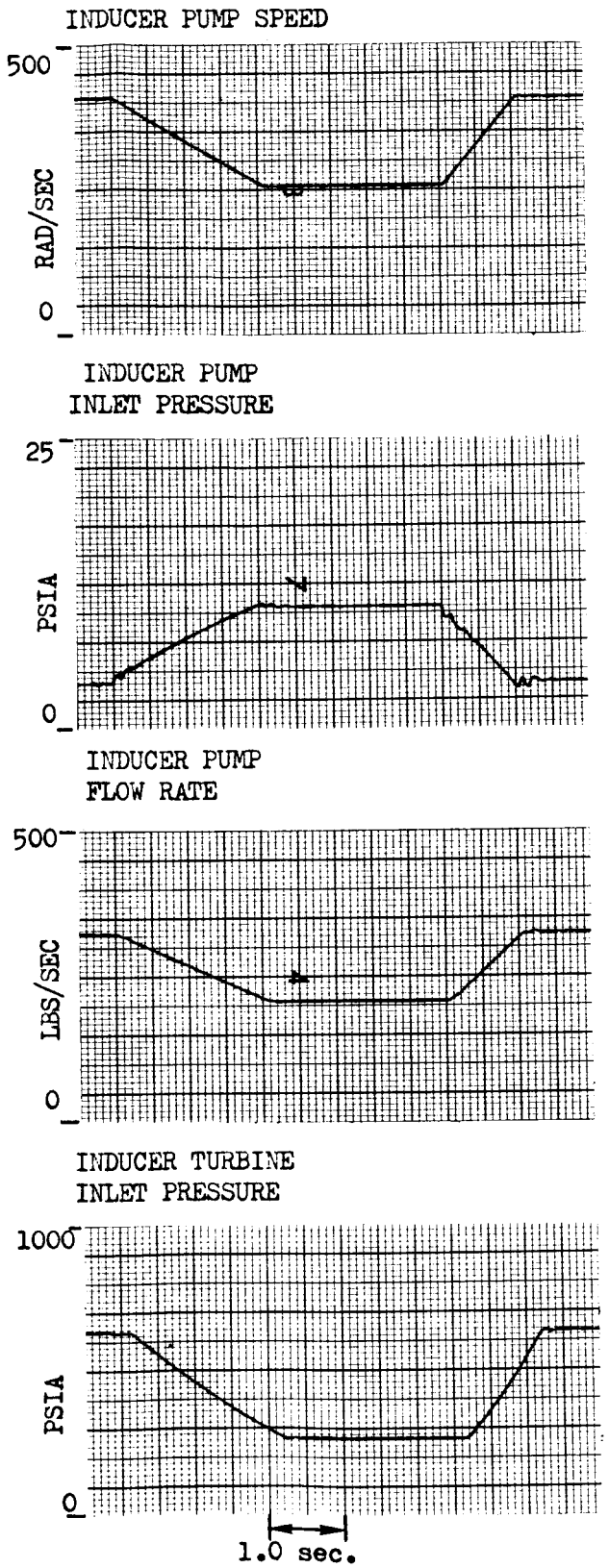


Figure 67. Close-Coupled Test Throttling, 2.0-Second Deceleration, 1.0-Second Acceleration

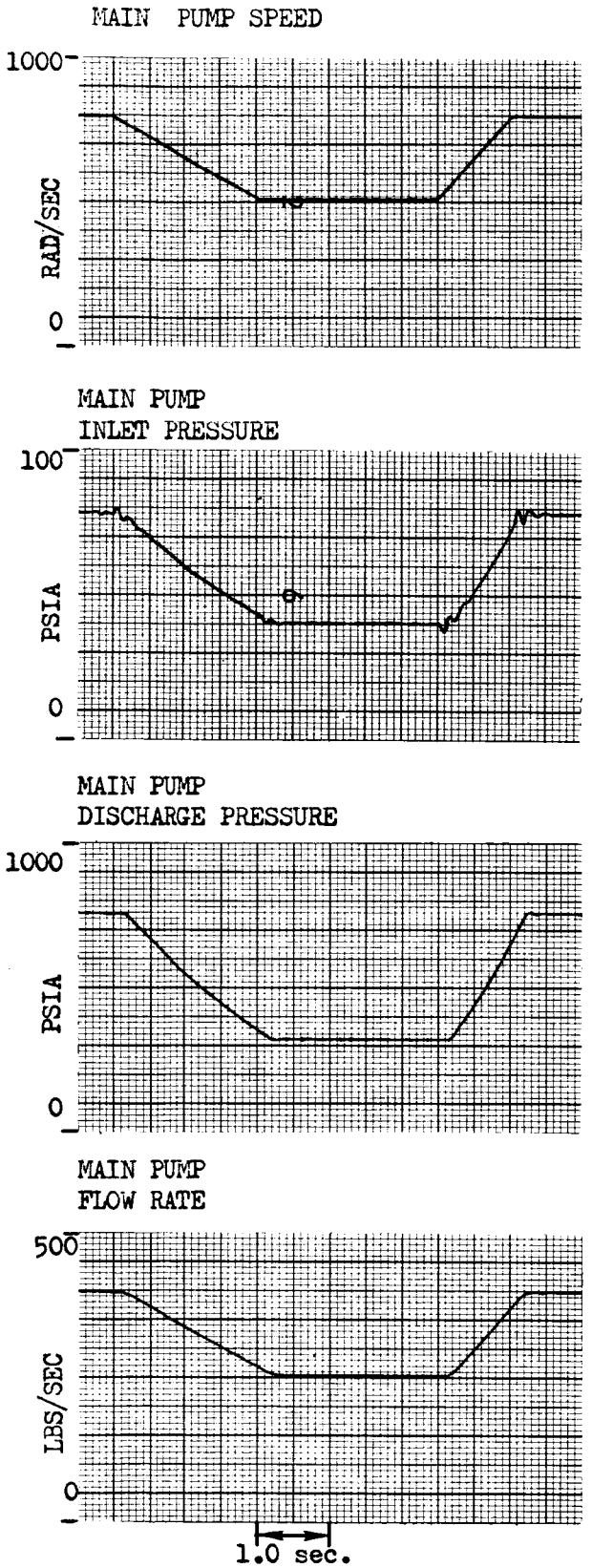


Figure 68. Close-Coupled Test Throttling, 2.0-Second Deceleration, 1.0-Second Acceleration

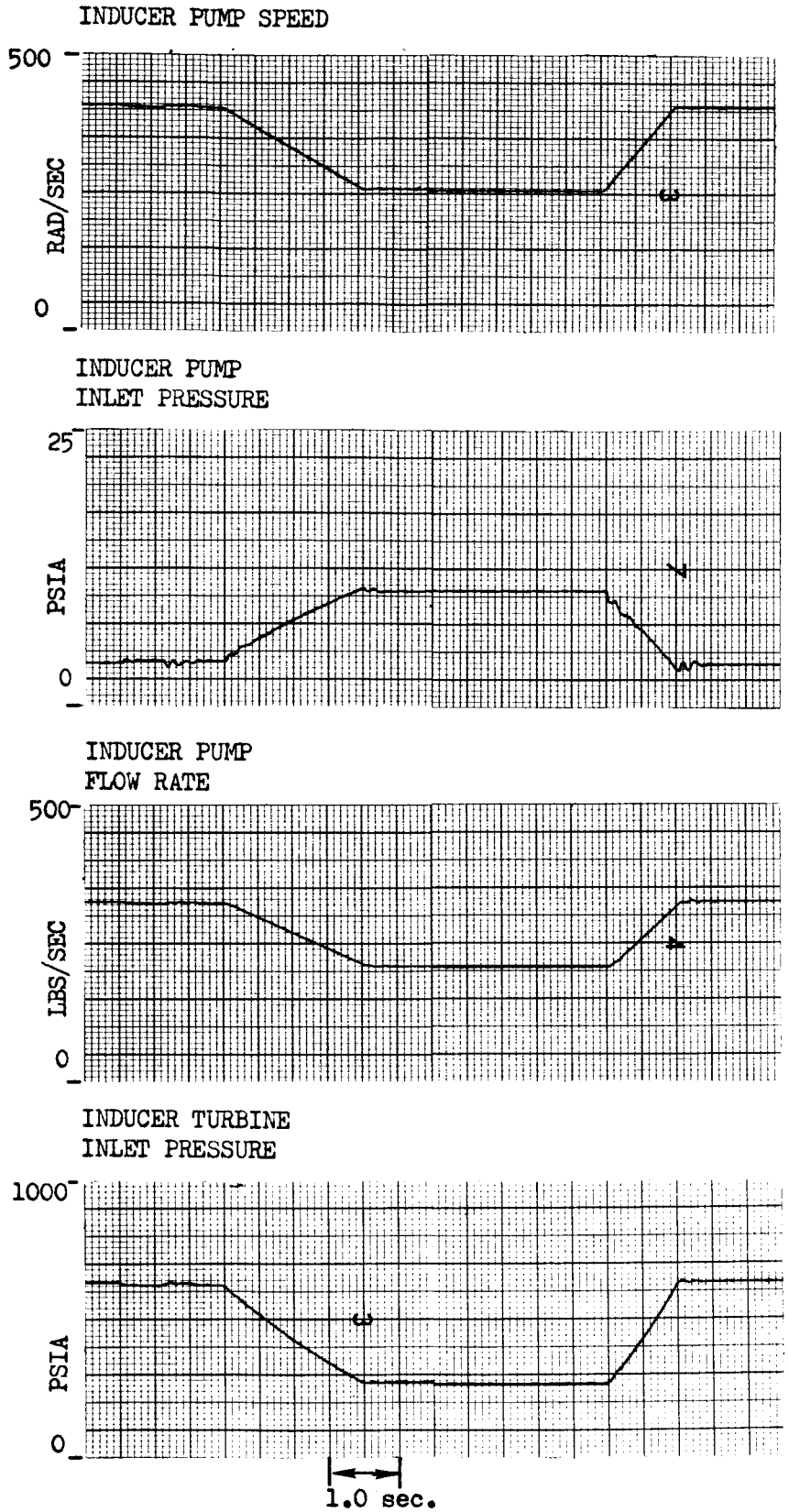


Figure 69. Remote-Coupled Test Throttling, 2.0-Second Deceleration, 1.0-Second Acceleration

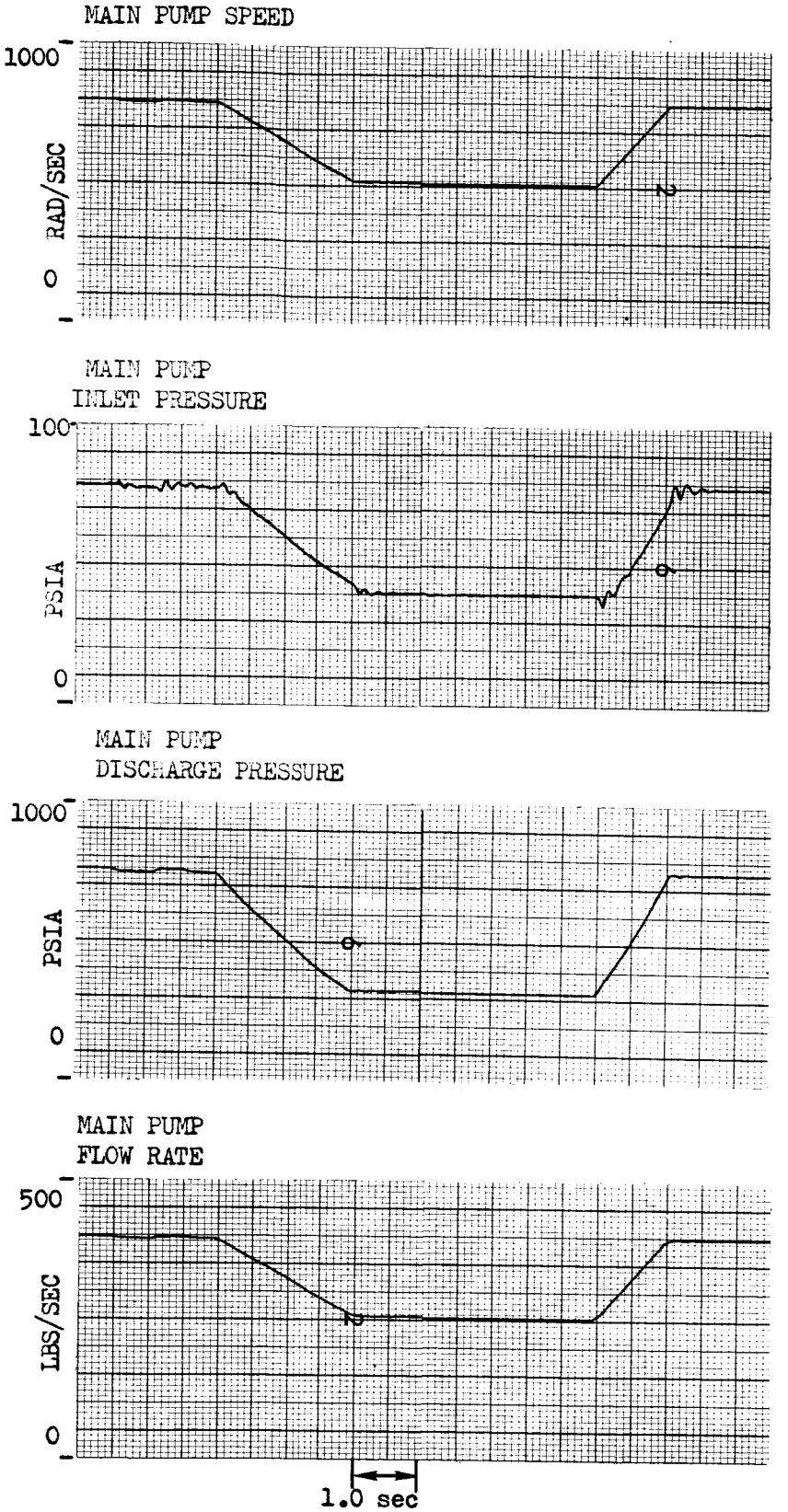


Figure 70. Close-Coupled Test Throttling, 2.0-Second Deceleration, 1.0-Second Acceleration

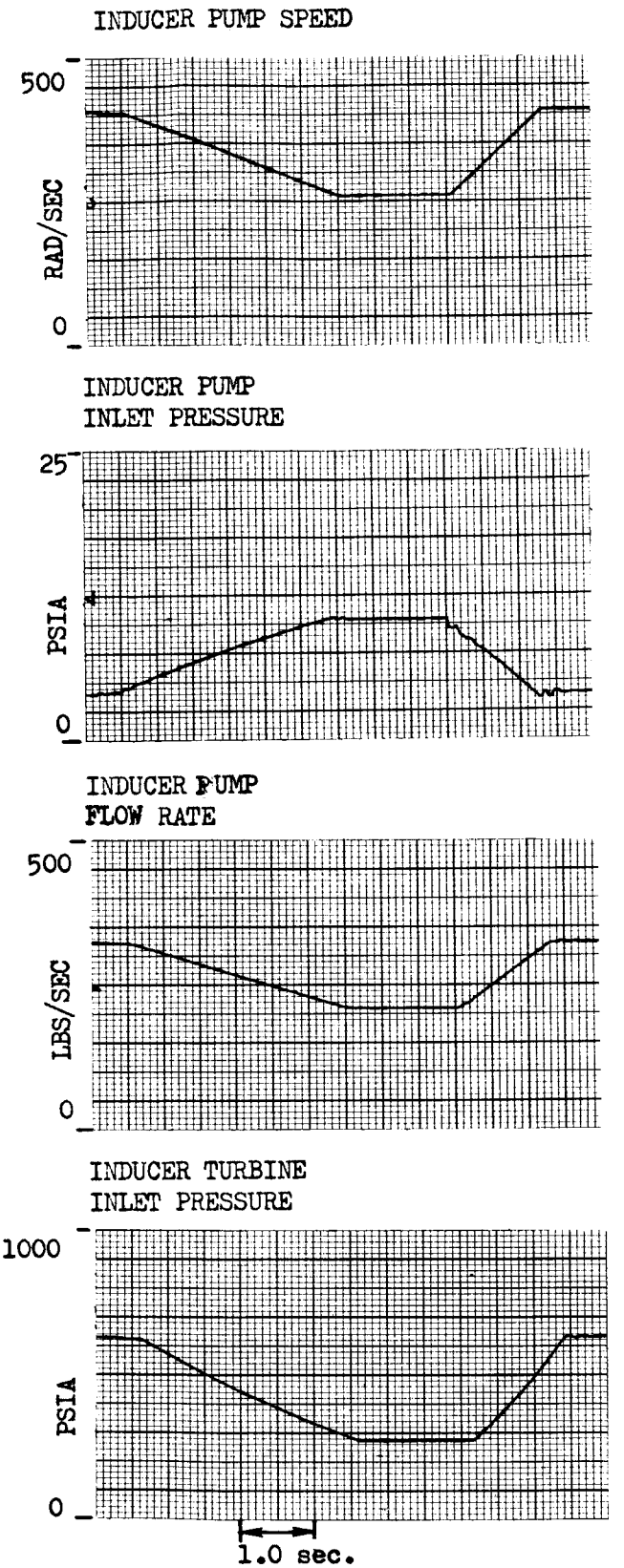


Figure 71. Close-Coupled Test Throttling, 3.0-Second Deceleration, 1.5-Second Acceleration

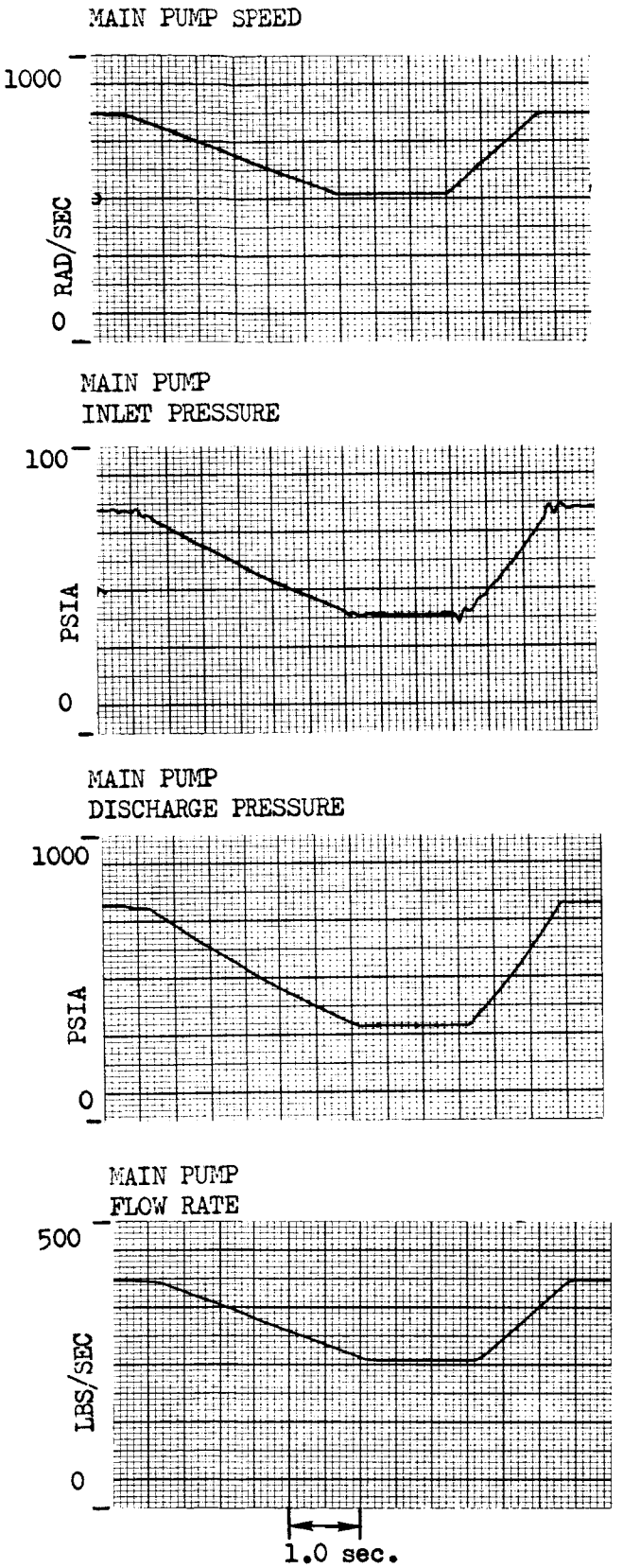


Figure 72. Close-Coupled Test Throttling, 3.0-Second Deceleration, 1.5-Second Acceleration

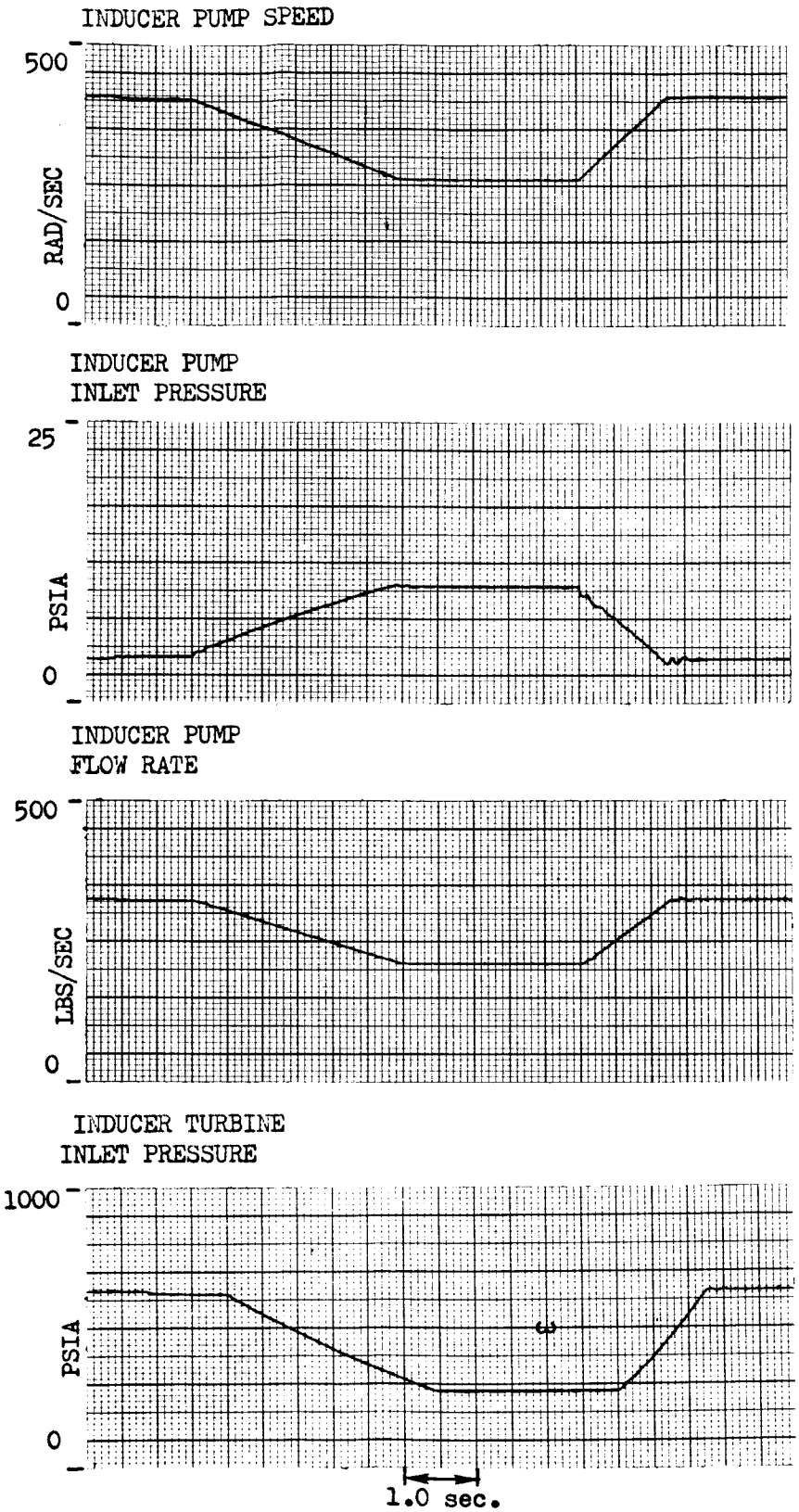


Figure 73. Remote-Coupled Test Throttling, 3.0-Second Deceleration, 1.5-Second Acceleration

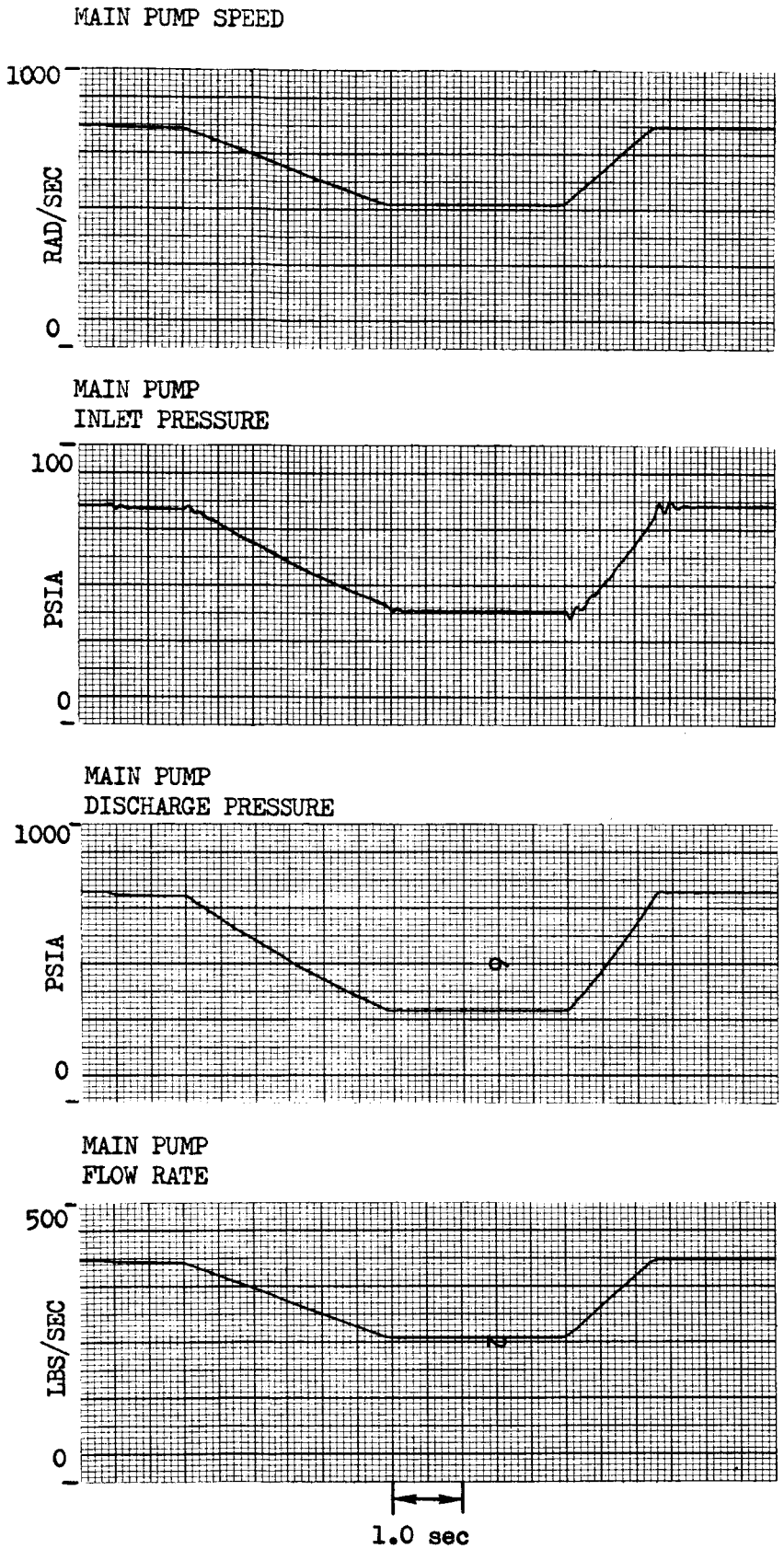


Figure 74. Remote-Coupled Test Throttling, 3.0-Second Deceleration, 1.5-Second Acceleration

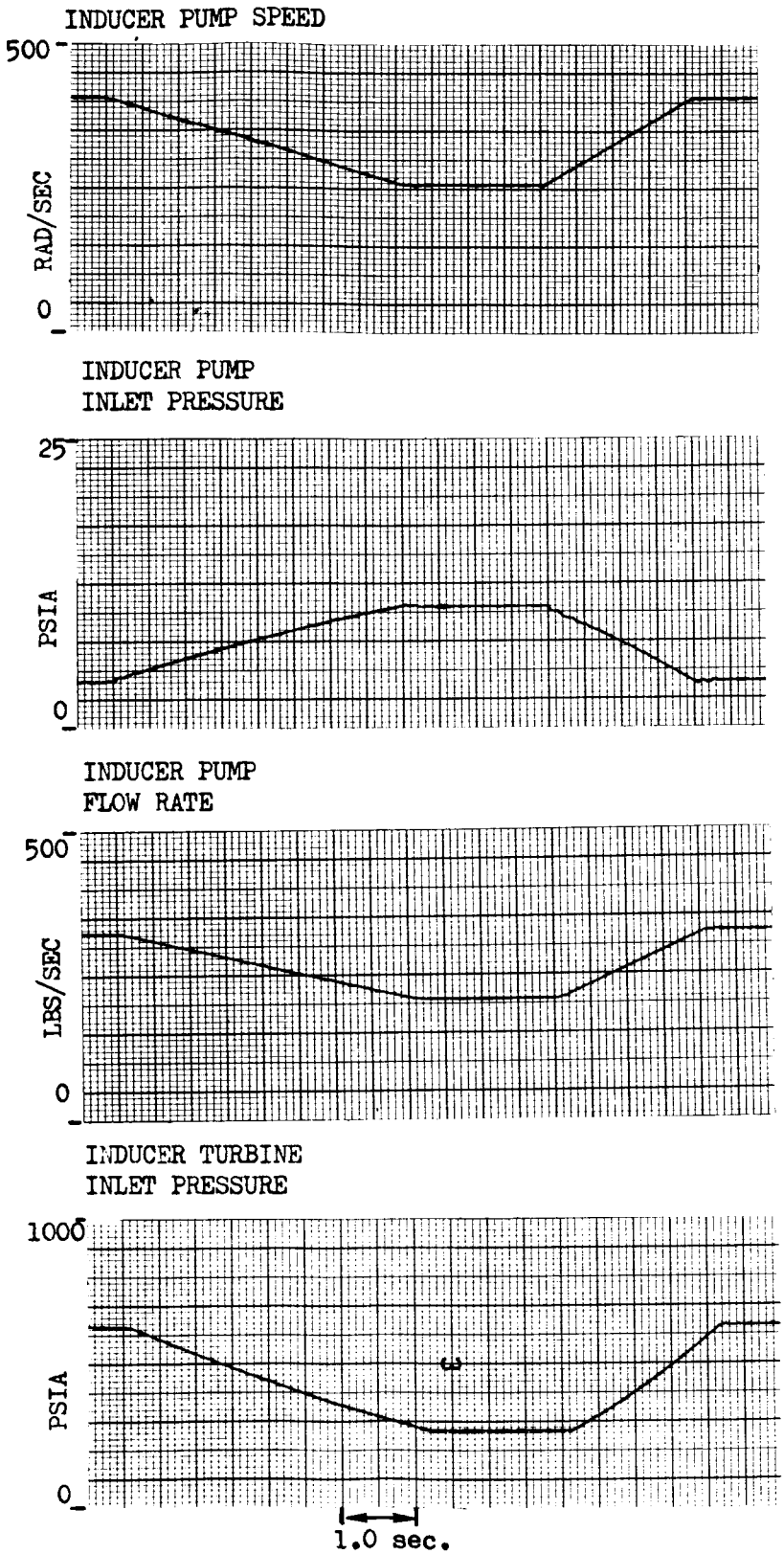


Figure 75. Close-Coupled Test Throttling, 4.0-Second Deceleration, 2.0-Second Acceleration

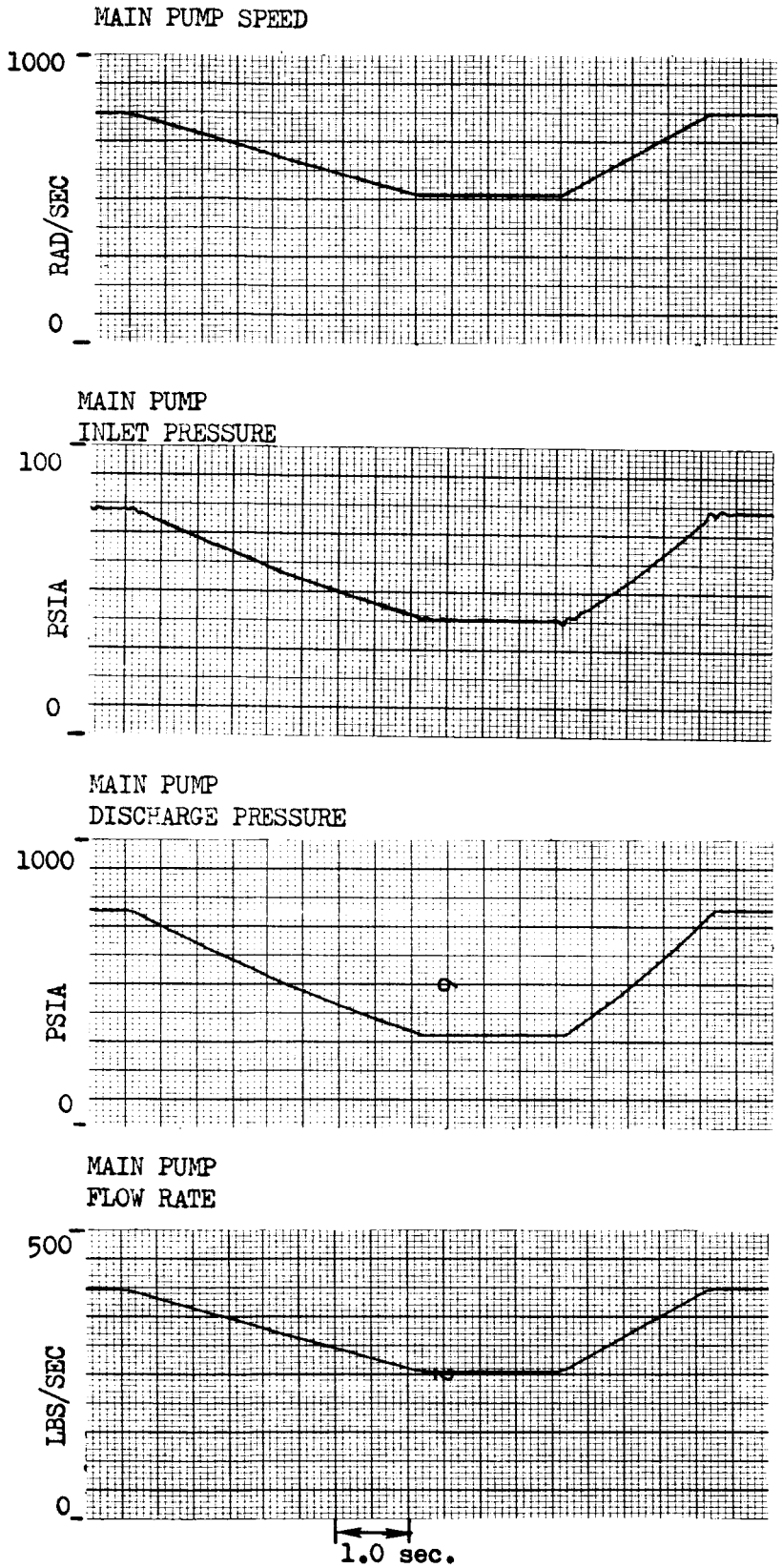


Figure 76. Close-Coupled Test Throttling, 4.0-Second Deceleration, 2.0-Second Acceleration

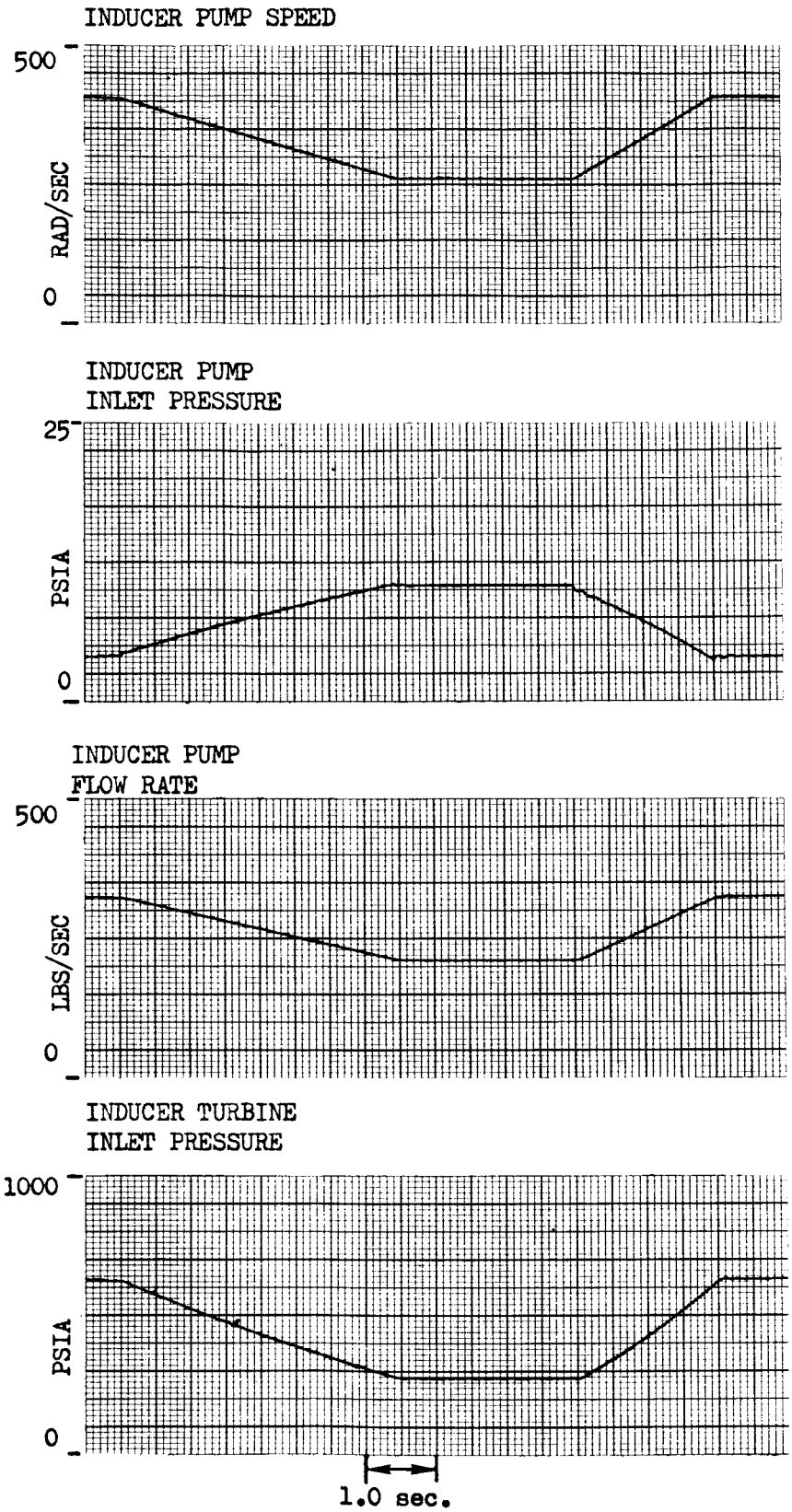


Figure 77. Remote-Coupled Test Throttling, 4.0-Second Deceleration, 2.0-Second Acceleration

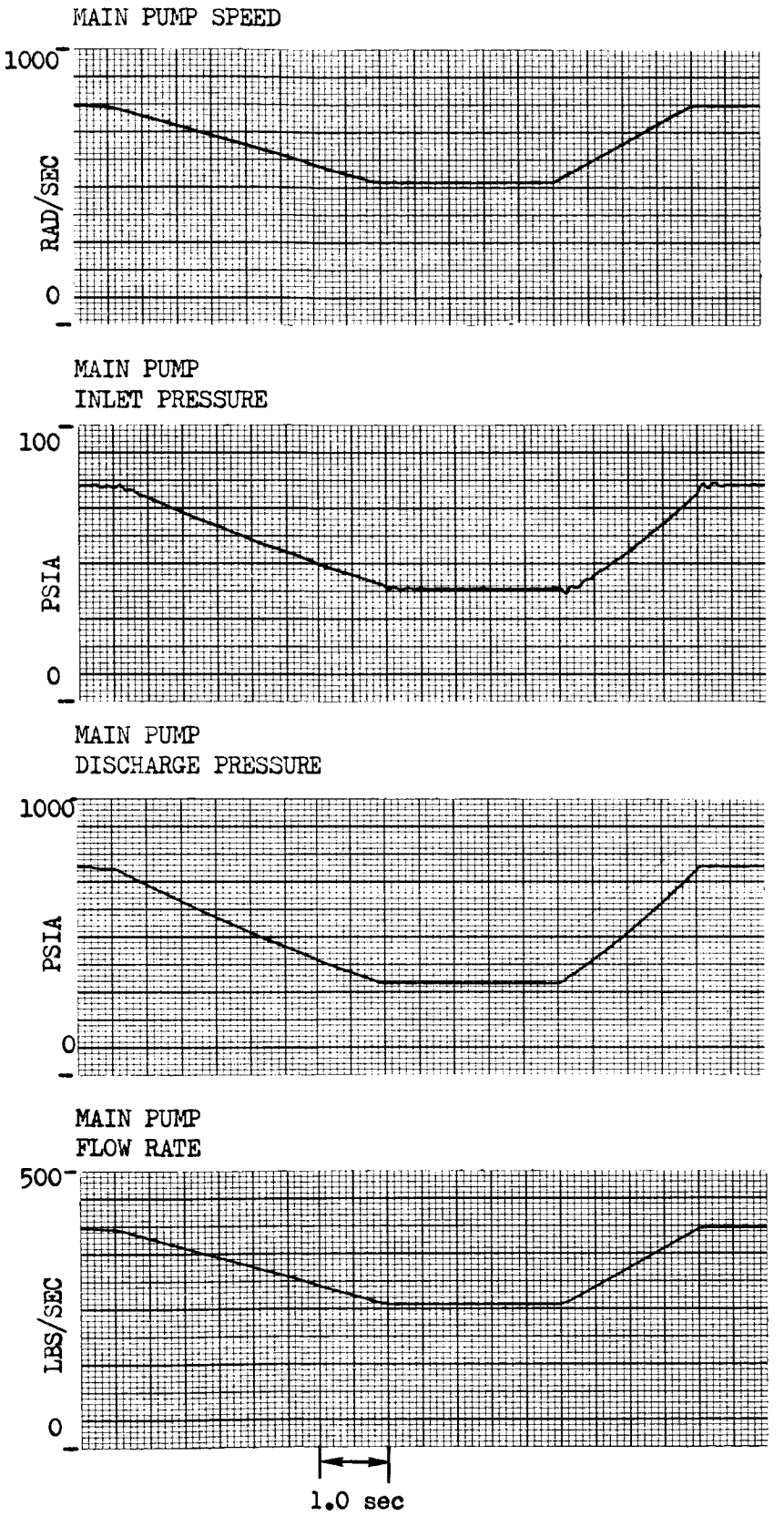


Figure 78. Remote-Coupled Test Throttling, 4.0-Second Deceleration, 2.0-Second Acceleration

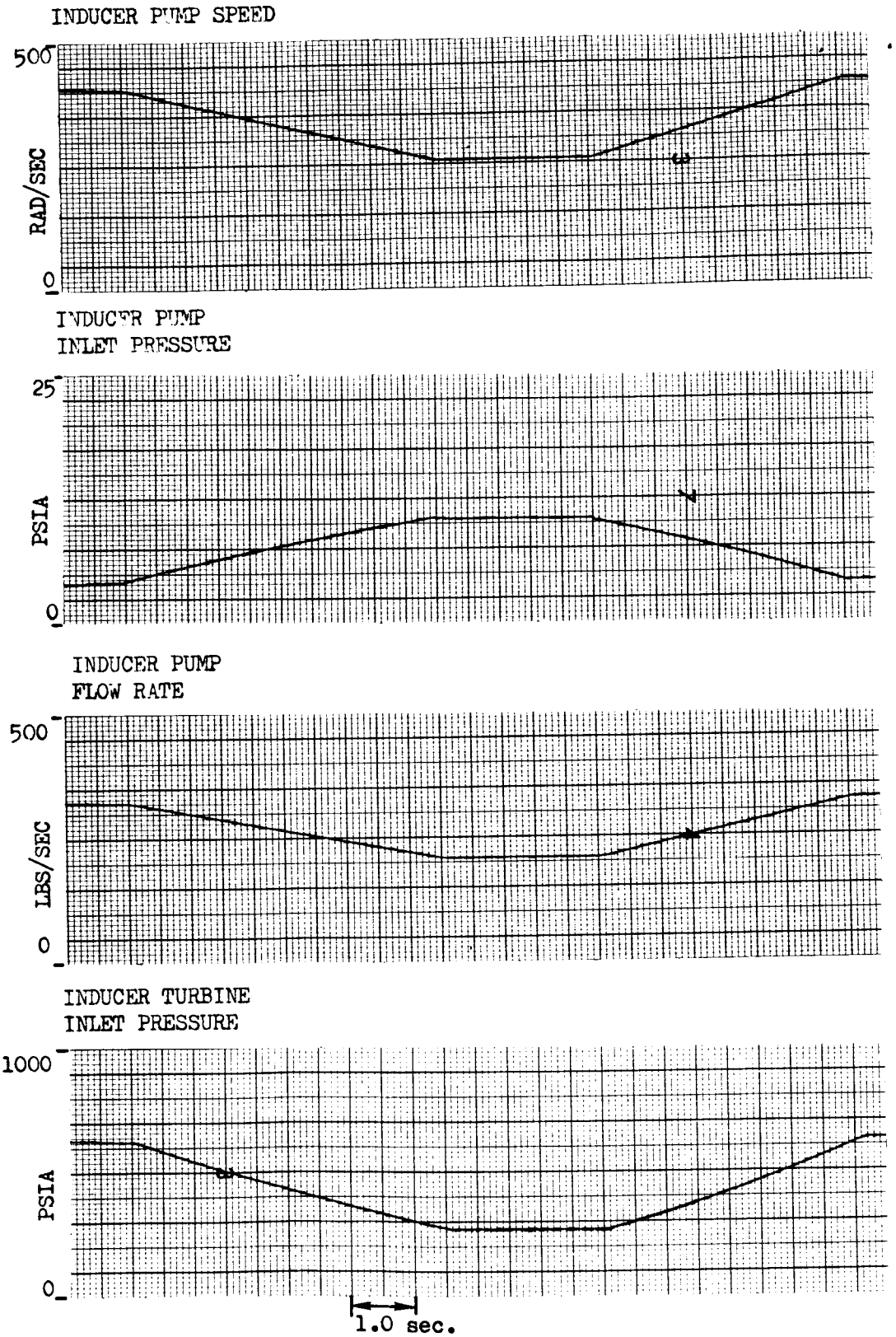


Figure 79. Close-Coupled Test Throttling, 5.0-Second Deceleration, 4.0-Second Acceleration

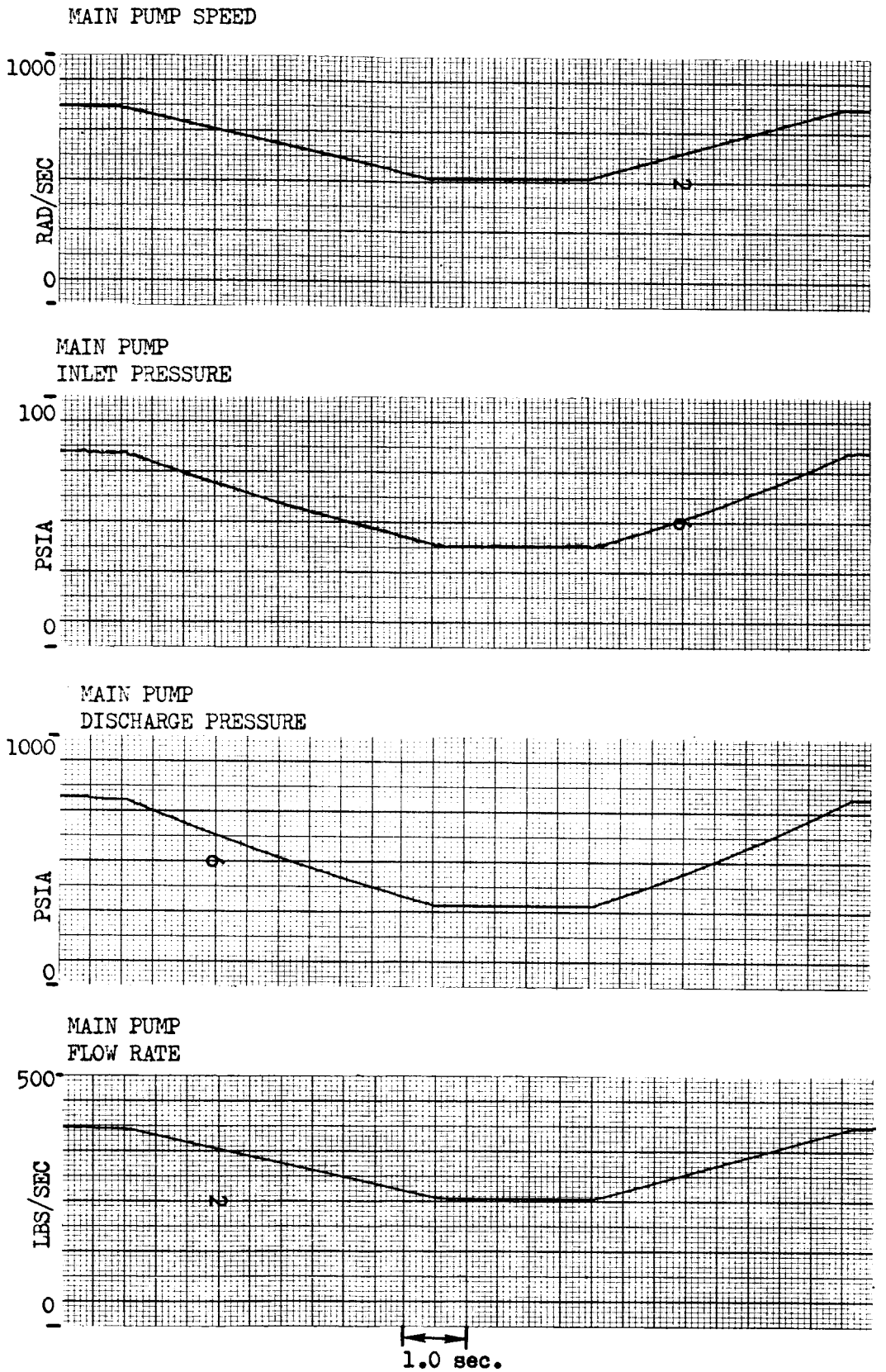


Figure 80. Close-Coupled Test Throttling, 5.0-Second Deceleration, 4.0-Second Acceleration

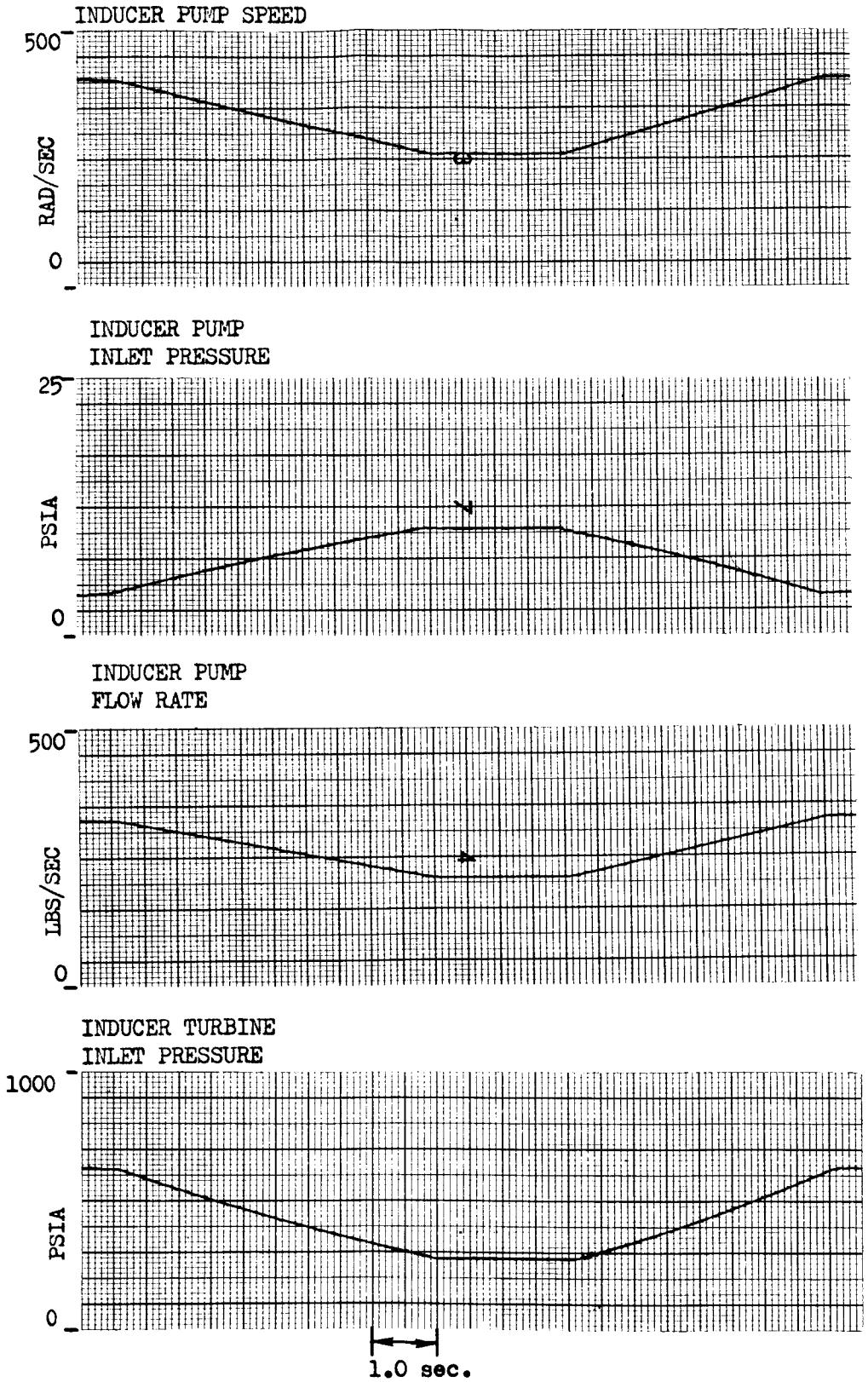


Figure 81. Remote-Coupled Test Throttling, 5.0-Second Deceleration, 4.0-Second Acceleration

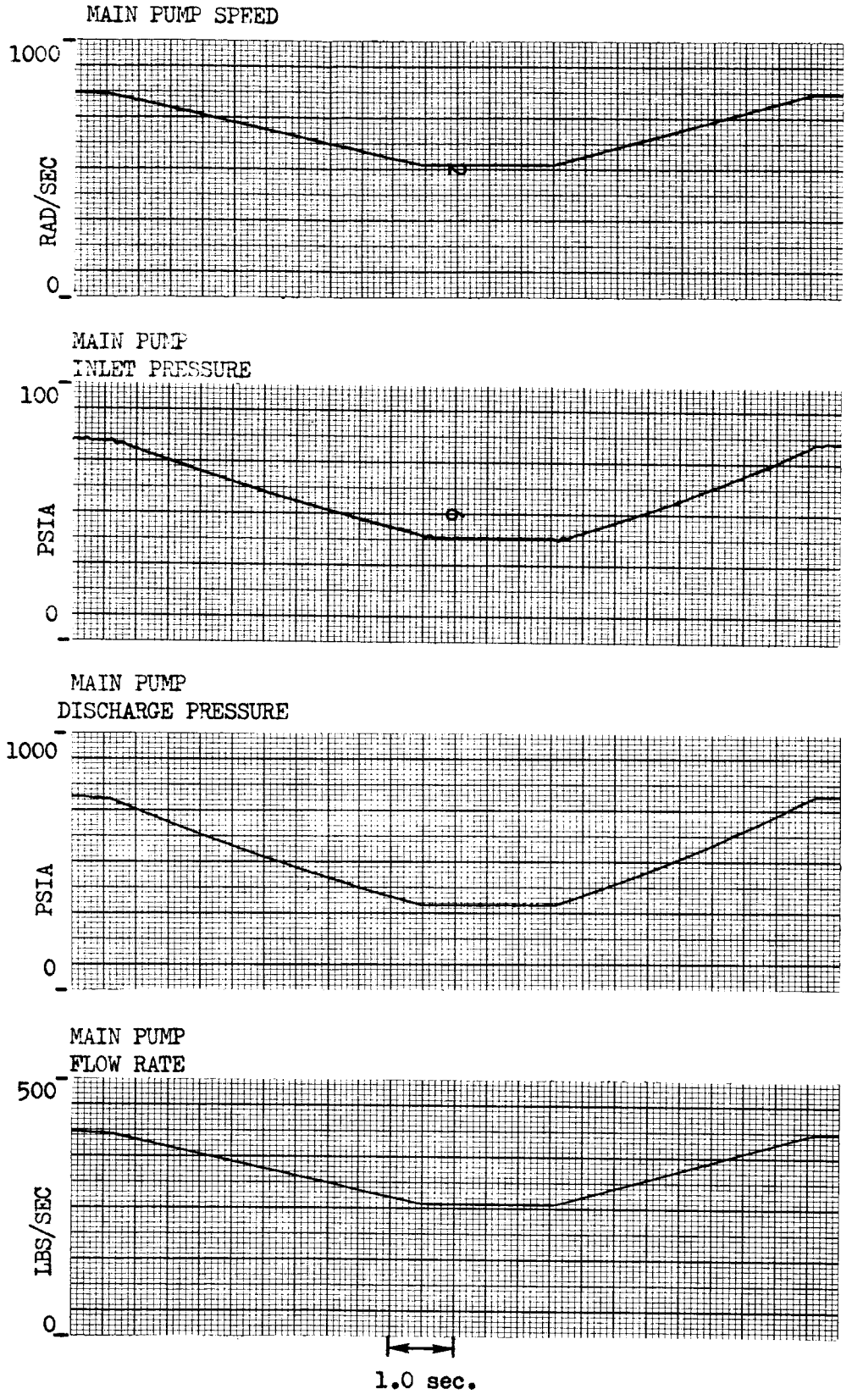


Figure 82. Remote-Coupled Test Throttling, 5.0-Second Deceleration, 4.0-Second Acceleration

ENGINE SYSTEM OPERATION

The final part of the parametric study involved consideration of the use of preinducers in an engine feed system pumping liquid oxygen and liquid hydrogen. To obtain this information, the digital computer model was used with modifications to simulate the engine configuration. The modifications included changing the preinducer inlet and main pump discharge systems to represent a J-2S engine installed in a Saturn S-IVB stage, and the use of a realistic hydrogen preinducer with the turbine drive tapped off at the main pump inducer discharge.

The oxidizer preinducer was close coupled to the main pump, and the inlet line was represented by 76 inches of 8-inch pipe, while the discharge system was represented by the resistance required to give rated flow conditions. The fuel preinducer was remote coupled with 93 inches of 10-inch pipe between the tank and preinducer inlet and 120 inches of 8-inch pipe between the preinducer discharge and main pump inlet. The hydrogen discharge system was represented by the resistance required to achieve rated flow operation. The oxidizer preinducer and main pump performance curves were the same as for the test hardware. The hydrogen preinducer and turbine performance curves are shown in Fig. 83 and 84, while the main hydrogen pump characteristics are those of the J-2 Mark 29-F shown in Fig. 85. The driving input to the main pumps was the pump speed vs time taken from a typical J-2S engine start, as shown in Fig. 86, along with the engine main valve sequencing.

The results of the LO_2 feed system simulation are presented in Fig. 87 and 88 for a preinducer NPSH of 25 and 16 feet, respectively. The 25-foot NPSH condition simulates the current J-2 starting condition without a preinducer. From the results of the two runs, there does not appear to be a problem with starting at 16 feet. Both starts exhibit pressure oscillations beginning at about 2.1 seconds because of the rapid opening of the oxidizer valve. The oscillations are more pronounced with 16 feet of NPSH, but the preinducer output is sufficient to prevent main pump cavitation. No attempt was made in this study to determine the effect

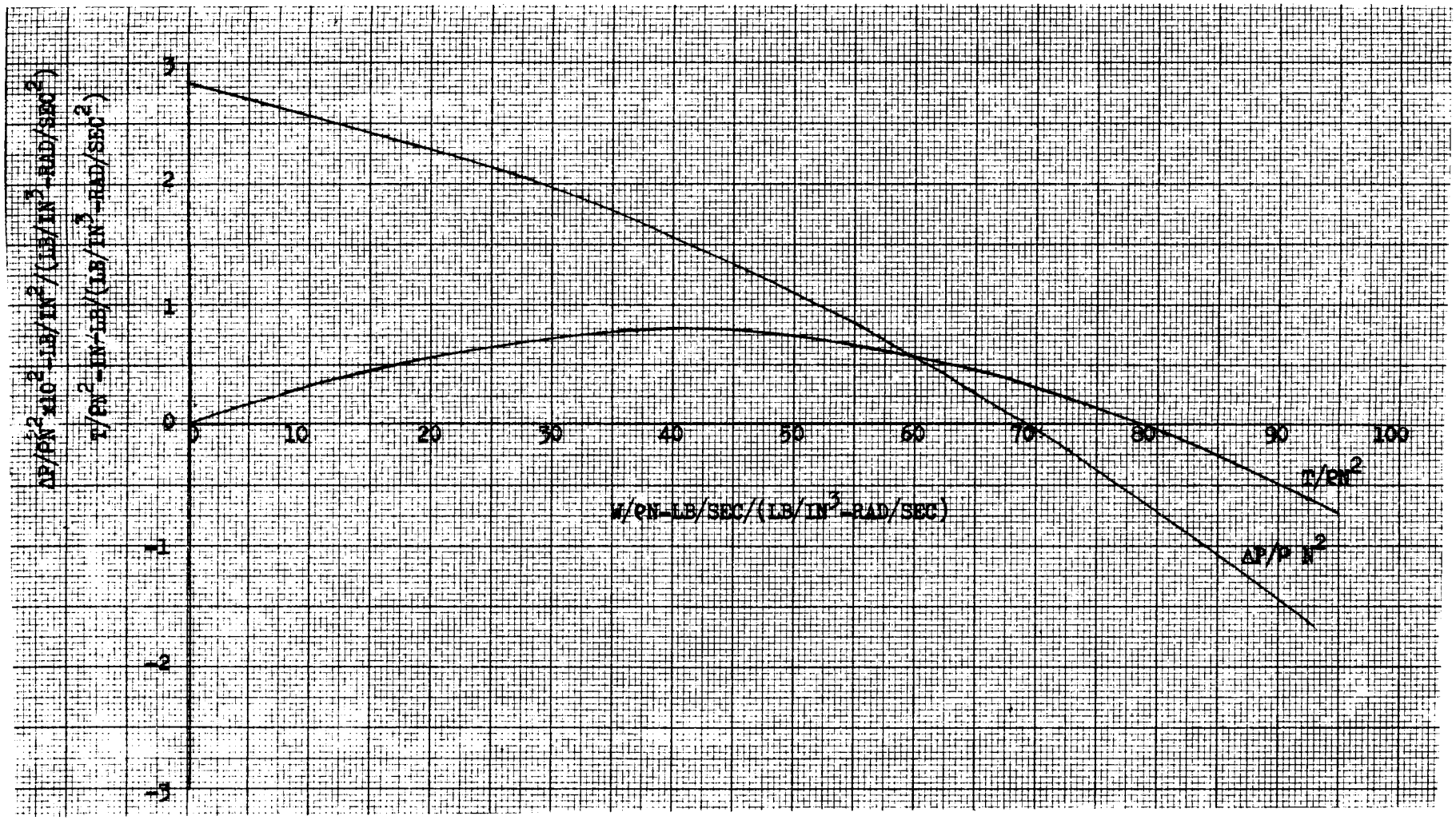


Figure 83. LH_2 Preinducer Performance

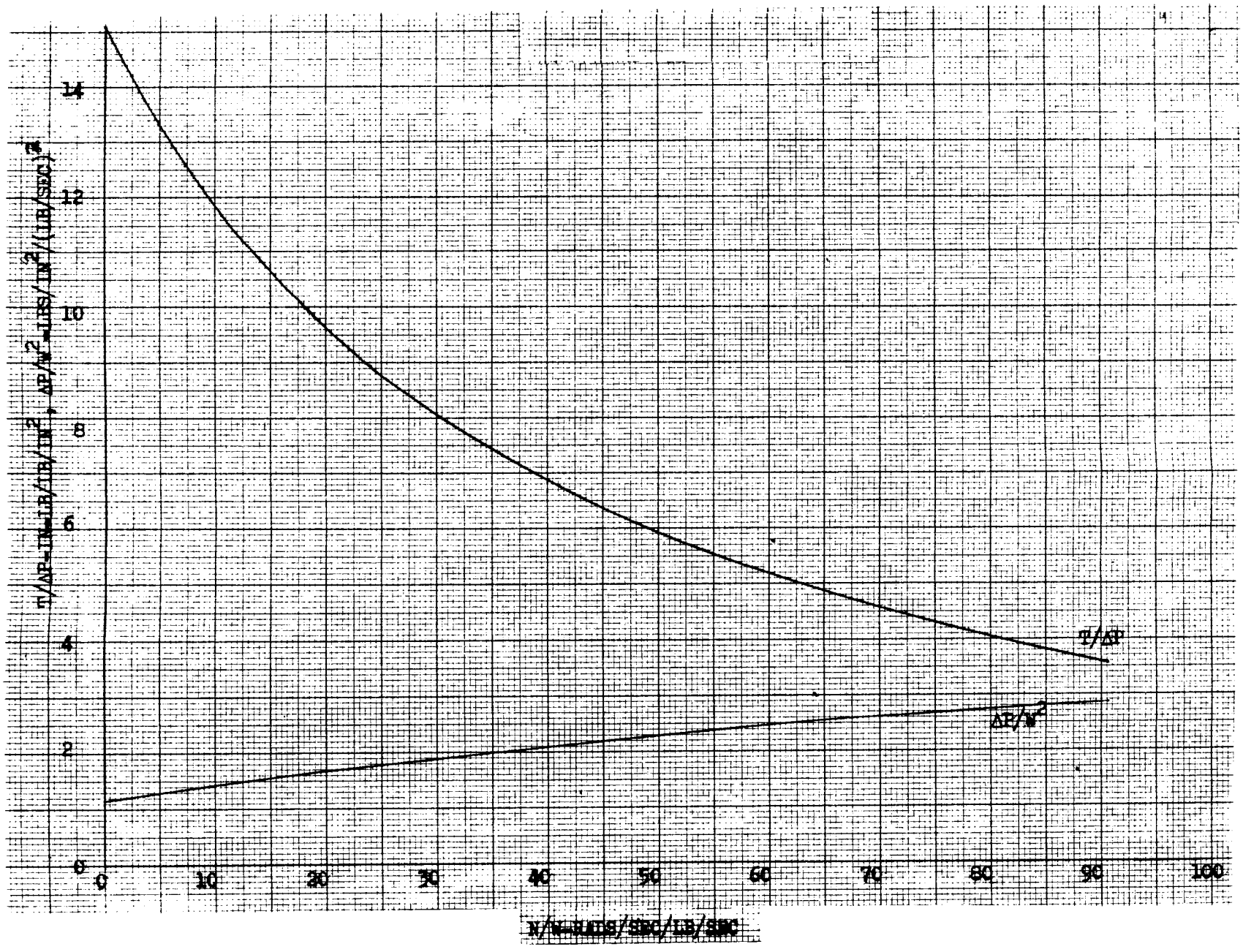


Figure 84. LH_2 Hydraulic Turbine Performance

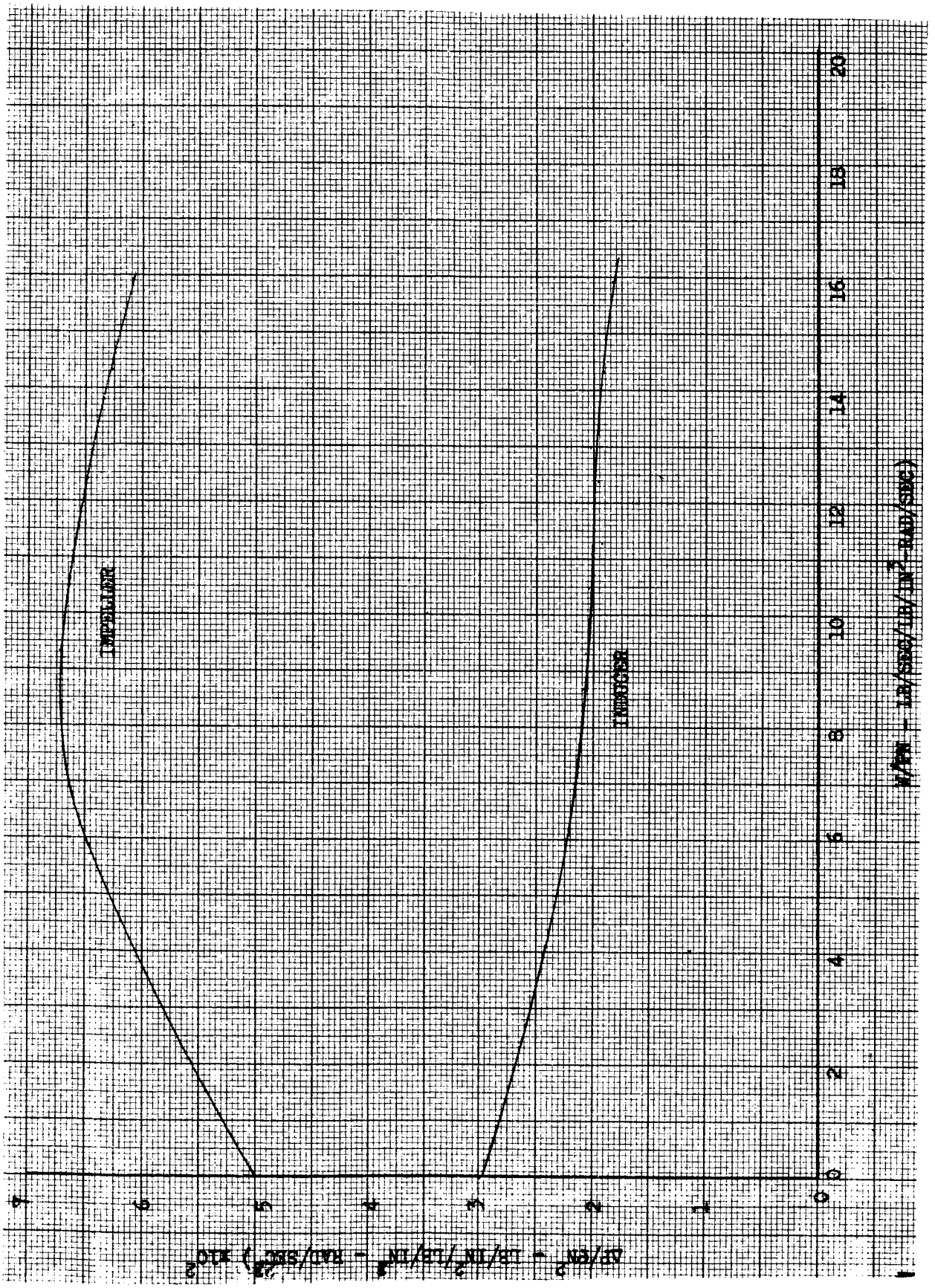


Figure 85. LH_2 Mark 29-F Pump Performance

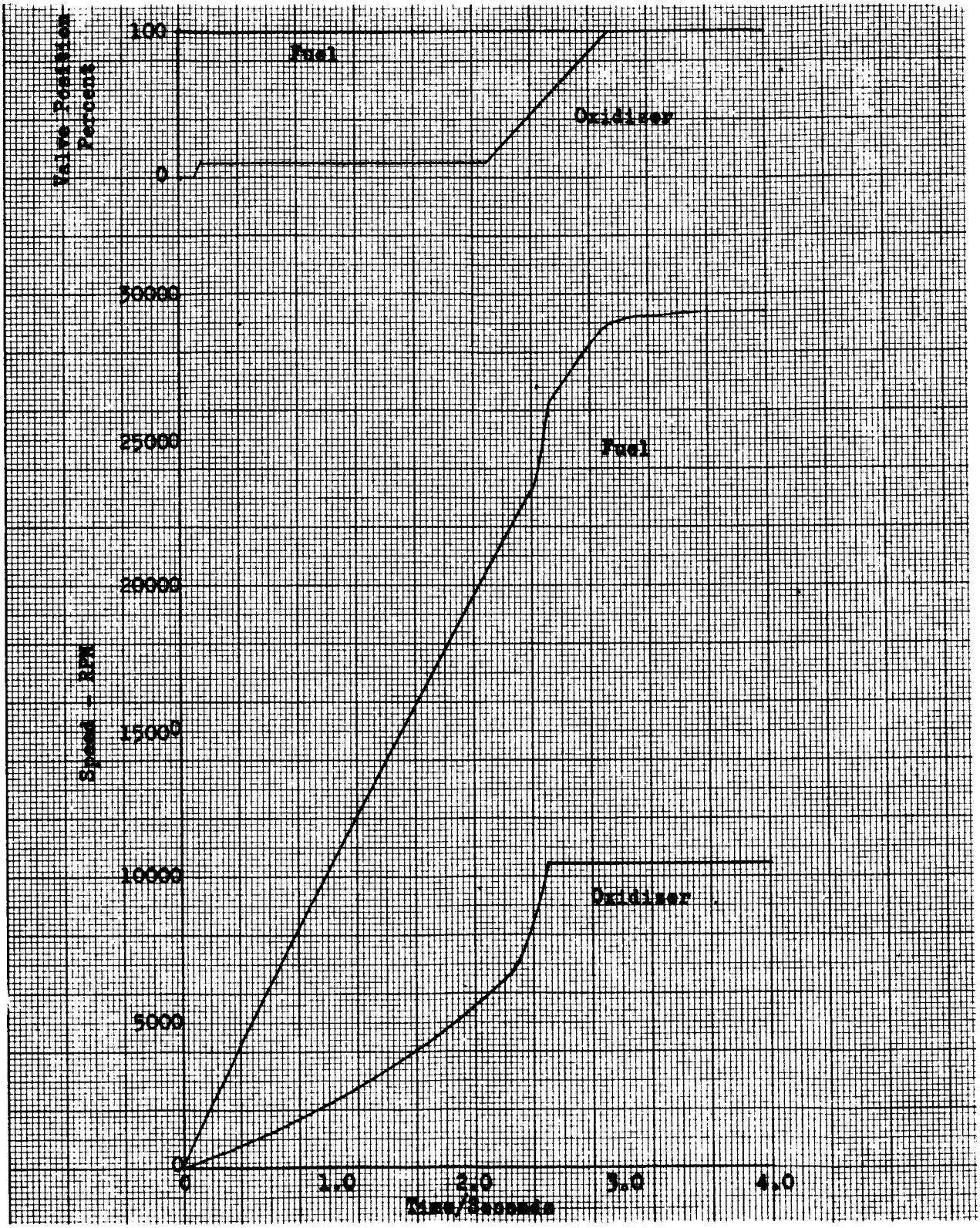


Figure 86. Typical J-2S Valve Sequencing and Pump Speed Buildup

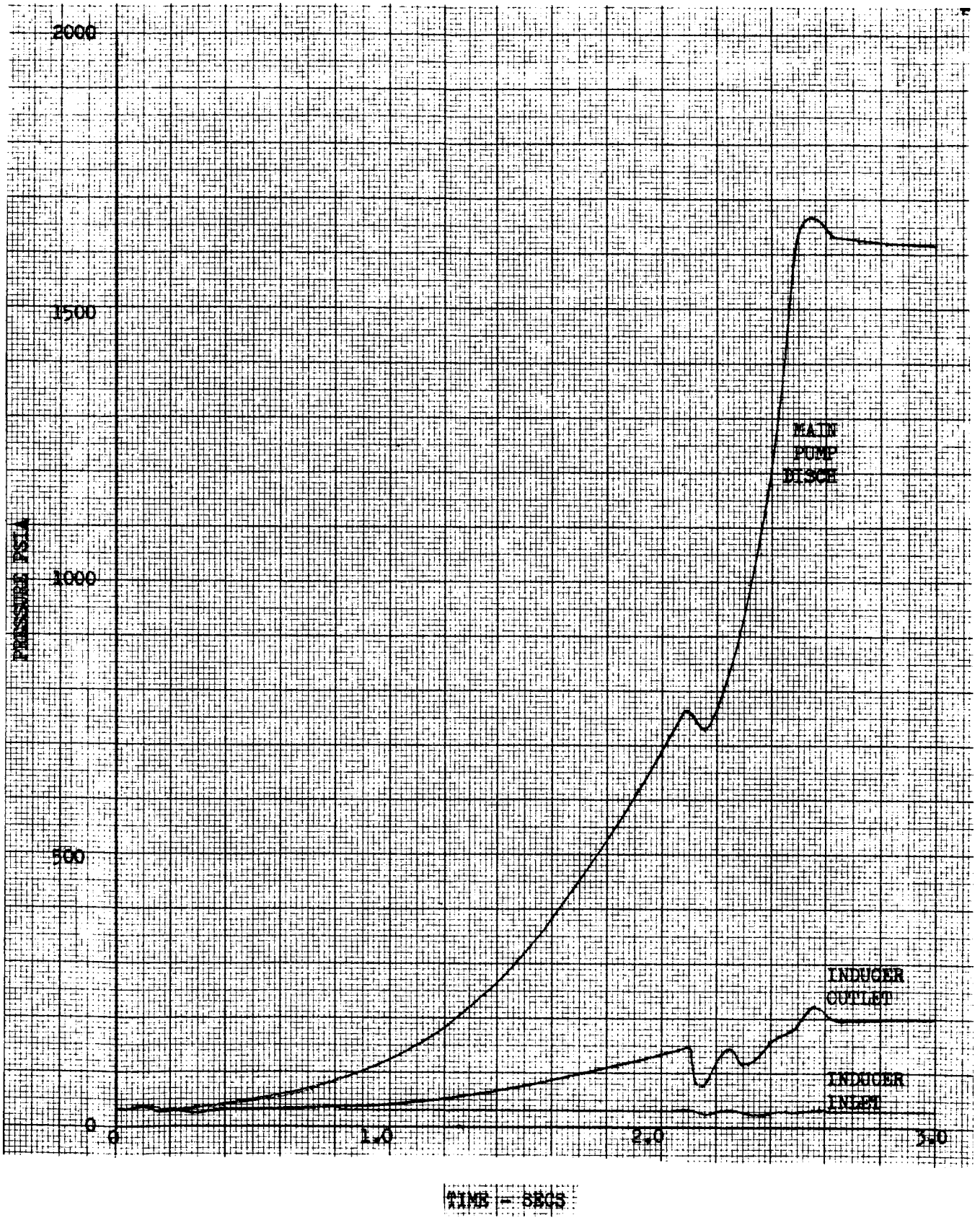


Figure 87. Simulated Oxidizer Engine Feed System, 25-Feet NPSH

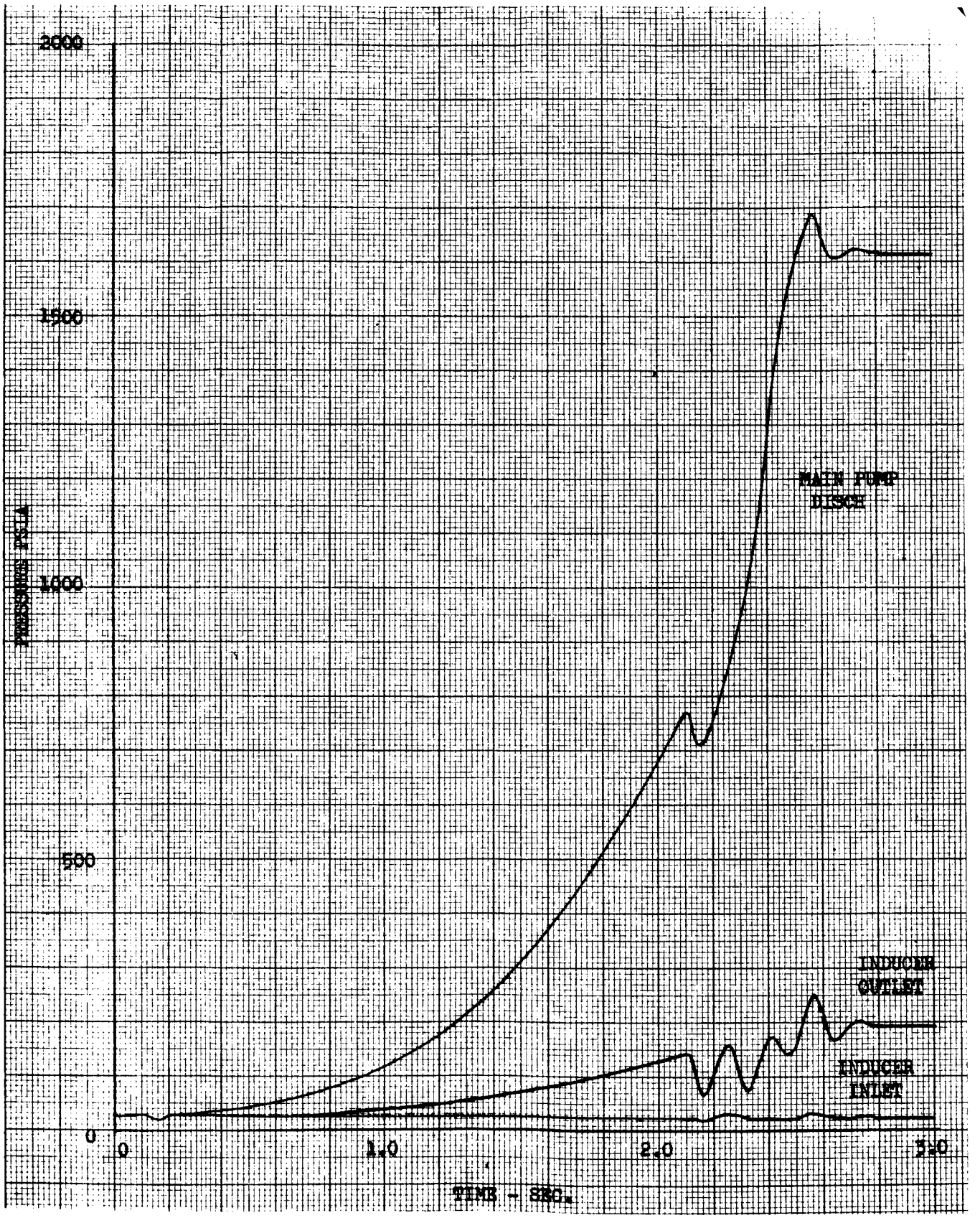


Figure 88. Simulated Oxidizer Feed System, 16-Feet NPSH

of varying the propellant valve sequencing. If the ramp opening portion of the oxidizer valve were slowed down, however, the magnitude of the oscillations would be reduced and the time to reach rated operation would be increased.

The results of the simulated fuel feed system are shown in Fig. 89. The start was run for an NPSH of 218 feet, representing current starting conditions. The start is smooth and there does not appear to be any reason why the NPSH could not be reduced. It should be noted that the depression of the fuel preinducer and pump pressures during the initial portion of the start are reduced compared to the oxidizer system because of the lower required fuel acceleration. The time to accelerate the flow is still 3.0 seconds, but the rated flowrate is only one-fifth of the oxidizer flowrate.

SUMMARY AND CONCLUSIONS

A series of parametric studies was made using the analog and digital computer models developed for predicting the dynamic performance of feed systems using a hydraulic turbine-driven preinducer in series with a high-head main pump. These studies covered the effects due to variation in preinducer design and test configuration, prediction of the planned test program performance, and predictions of start performance for an engine with preinducers used in the propellant feed systems.

From the results of these studies, the following conclusions are drawn:

1. The preinducer rotating moment of inertia has a significant effect upon the starting performance: the lower the inertia, the better the start.
2. The fluid inertia (ratio of line length to area) of the pump coupling line for a remote location of the preinducer has an effect upon the starting performance: the lower the inertia, the better the performance.

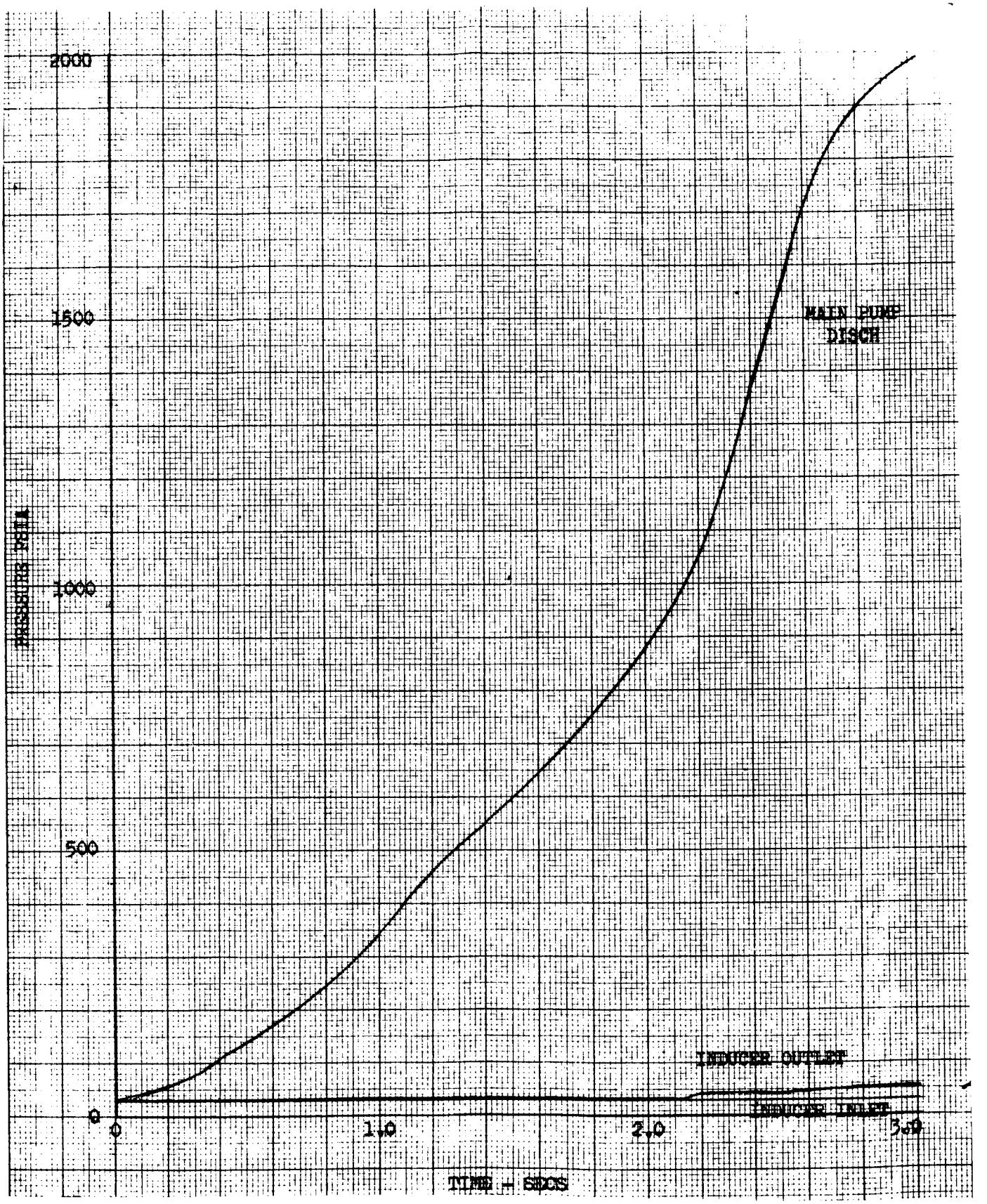


Figure 89. Simulated Fuel Feed System

3. The starting and throttling performance for the planned test series is smooth and shows little dynamic effects.

4. The use of this type of preinducer in an engine feed system is feasible, with a proper starting sequence, at low preinducer NPSH's, thereby allowing the use of lower tank pressures, and thus, reducing tank wall weights.

APPENDIX A

EQUATION NOMENCLATURE

A = line area, $in.^2$

a = acoustic velocity, in./sec or Eigen vectors for modal analysis

$1/C$ = pump compliance, $in.^{-2}$

g = acceleration of gravity, $in./sec^2$

I = turbopump moment of inertia, $in.-lb-sec^2$

L = length, inches, or fluid inertia, $sec^2/in.^2$

N = turbopump speed, rad/sec

NPSH = pump net positive suction head, feet

P = pressure, $lb/in.^2$

ΔP = pressure difference, $lb/in.^2$

R = resistance, $sec^2/in.^5$, or pump radius, inches

T = torque, in.-lb

t = time, seconds

Δt = computing interval (for digital model), seconds

$\dot{W}$ = flowrate, lb/sec

$\ddot{W}$ = flow acceleration, lb/sec^2

γ = time delay line parameter, $sec/in.^2$

φ = pump flow parameter

ψ = pump head parameter

χ = pump torque parameter

ρ = fluid density, $lb/in.^3$

σ = cavitation parameter

τ = time delay line transmission time, seconds

ω = undamped natural frequency

V = modal analysis parameter

ξ = modal damping constant

BASIC EQUATIONS

A. Tank and Tube Bundle

$$P_{ILI(t)} = P_T + L_T \rho - \frac{R_{TB}}{\rho} (\dot{W}_{ILI})^2 \quad (1)$$

Note: L_T is fluid height in tank

B. Inducer Inlet Line

1. Time Delay Equations

$$\tau_{IL} = L_{IL}/a_{IL}$$

$$\gamma_{IL} = a_{IL}/g\, A_{IL}$$

$$P_{ILI(t)} = P_{IPI(t - \tau_{IL})} + \gamma_{IL} \left[\dot{W}_{ILI(t)} - \dot{W}_{ILO(t - \tau_{IL})}\right] + \frac{R_{ILI}}{\rho} \left[\dot{W}_{ILI(t)}\right]^2 + \frac{R_{ILO}}{\rho} \left[\dot{W}_{IL(t - \tau_{IL})}\right]^2 \quad (2)$$

$$P_{IPI(t)} = P_{ILI(t - \tau_{IL})} - \gamma_{IL} \dot{W}_{ILO(t)} - \dot{W}_{ILI(t - \tau_{IL})} - \frac{R_{ILO}}{\rho} \left[\dot{W}_{ILO(t)}\right]^2 - \frac{R_{ILI}}{\rho} \left[\dot{W}_{ILI(t - \tau_{IL})}\right]^2 \quad (3)$$

2. Modal Equations

$$\frac{L_{IL}}{gA_{IL}} \ddot{W}^* + \frac{R_{IL}}{\rho} \dot{W}^{*2} = P_{ILI(t)} - P_{IPI(t)}$$

$$\ddot{V}_i + 2\xi \omega_i \dot{V}_i + \omega_i^2 V_i = a_{1i} P_{ILI(t)} - a_{ni} P_{IPI(t)} \quad (4)$$

(i = 2 to number of modes)

Note: $\dot{W}^*$ is first mode flowrate

$$\dot{W}_{ILI(t)} = \dot{W}^* + \sum_{i=2}^{n} a_{1i} \dot{V}_i \tag{5}$$

$$\dot{W}_{ILO(t)} = \dot{W}^* + \sum_{i=2}^{n} a_{1i} \dot{V}_i \tag{6}$$

C. Inducer Inlet Compliance

$$NPSH_{IP} = (P_{IPI} - P_{VAP})/(12)\ (\rho) \tag{7}$$

$$\sigma_{IP} = \frac{NPSH_{IP}\ (12)\ (2g)}{(N_{IP})^2\ (R_{IP})^2\ (1 + (\varphi_{IP})^2)} \tag{8}$$

$$P_{IPI(t)} = P_{IPI(t - \Delta t)} + \left(\frac{1}{C_l}\right)_{IP} \left[W_{ILO(t)} - W_{IP(t)}\right] \Delta t \tag{9}$$

D. Inducer Pump

1. Head

$$\varphi_{IP} = \dot{W}_{IP}/\rho\ (N_{IP})\ (R_{IP})\ (A_{IP}) \tag{10}$$

$$\psi_{IP} = f(\varphi_{IP})$$

For digital simulation, ψ_{IP} will be evaluated by linear interpolation between points representing the curve.

$$\overline{\Delta P_{IP}} = (\psi_{IP})\ (\rho)\ (N_{IP})^2\ \frac{(R_{IP})^2}{g}\ \text{(noncavitating)} \tag{11}$$

Cavitation Correction

$$\frac{\Delta P}{\overline{\Delta P}_{IP}} = f\left[\left(\frac{NPSH}{N^2}\right)_{IP},\ \varphi_{IP}\right]$$

$$\Delta P_{IP} = \left[\frac{\Delta P}{\Delta P}\right]_{IP} (\overline{\Delta P}_{IP}) \tag{12}$$

Note: $\dot{W}^*$ is first mode flowrate

$$P_{IPD} = P_{IPI} + \Delta P_{IP} - \frac{L_{IP}}{\Delta t}\left[\dot{W}_{IP(t)} - \dot{W}_{IP(t-\Delta t)}\right] \quad (13)$$

2. Torque

$$\chi_{IP} = f(\varphi_{IP})$$

$$\overline{T_{IP}} = \chi_{IP}\ (\rho)\ (N_{IP})^2\ (R_{IP})^3\ (A_{IP})/g \quad (14)$$

$$T_{IP} = \overline{T_{IP}}\ \left(\frac{\Delta P}{\overline{\Delta P}}\right) IP \quad (15)$$

E. Inducer Turbine

1. Head-Capacity for Liquid Drive Fluid

$$\Delta P_{IT} = \frac{0.00307}{\rho}\ \dot{W}_{IT}^{\ 2} \quad (16)$$

2. Torque for Liquid Drive Fluid

$$(T/\Delta P)_{IT} = f(N_{IP})$$

$$T_{IT} = (T/\Delta P)_{IT}\ (\Delta P)_{IT} \quad (17)$$

F. Inducer Speed

$$N_{IP} = N_{IP} + 1/I_{ITP}\ (T_{IT} - T_{IP})\ \Delta t \quad (18)$$

G. Inducer Turbine Inlet Line

1. Lumped Parameter

$$P_{ITVD(t)} - P_{ITI(t)} = \frac{L_{ITL}}{A_{ITL}}\ \frac{d\ WIT}{d\ t} \quad (19)$$

2. Modal Equations

$$\left(L_{ITL}/gA_{ITL}\right)\dot{W}_{ITL} + \frac{R_{ITL}}{\rho}\left(\dot{W}^*_{ITL}\right)^2 = P_{ITVD} - P_{ITI} \tag{20}$$

$$\ddot{V}''_i + 2\xi\,\omega''_i\,\dot{V}''_i + \omega''^2_i\,V''_i = a''_{1i}\,P_{ITVD} - a''_{ni}\,P_{ITI}$$

$$\dot{W}_{ITV(t)} = \dot{W}^*_{ITL} + \sum_{i=2}^{n} a''_{1i}\,\dot{V}''_i \tag{21}$$

$$\dot{W}_{IT(t)} = \dot{W}^*_{ITL} + \sum_{i=2}^{n} a''_{ni}\,\dot{V}''_i \tag{22}$$

H. Inducer Turbine Line Value

$$P_{ITVD} = P_{PD} - \frac{R_{ITV}}{\rho}\left(\dot{W}_{ITV(t)}\right)^2 \tag{23}$$

I. Inducer-Main Pump Coupling

$$\dot{W}_P = \dot{W}_{DL} + \dot{W}_{ITV} \tag{24}$$

1. If Close Coupled

$$P_{PI} = P_{IPD}$$

2. If Line Coupled (assuming line length >10 feet)

A. Time-Delay Equations

$$\tau_{PIL} = L_{PIL}/a_{PIL}$$

$$\gamma_{PIL} = a_{PIL}/gA_{PIL}$$

$$P_{IPD(t)} = P_{PI(t-\tau_{PIL})} + \gamma_{PIL}\left(\dot{W}_{PIL(t)} - \dot{W}_{PIL(t-\tau_{PIL})}\right) + \frac{R_{PILI}}{\rho}\left(W_{PIL(t)}\right)^2 + \frac{R_{PILO}}{\rho}\left(W_{PI(t-\tau_{PI})}\right)^2 \tag{25}$$

$$P_{PI(t)} = P_{IPD(t - \tau_{PIL})} - \gamma_{PIL} \left(\dot{W}_{PI(t)} - \dot{W}_{PI(t - \tau_{PIL})} \right) -$$

$$\frac{R_{PIL0}}{\rho} \left(\dot{W}_{PI(t)} \right)^2 - \frac{R_{PILI}}{\rho} \left(\dot{W}_{PIL(t - \tau_{PIL})} \right)^2 \qquad (26)$$

B. Modal Equations

$$\left[\frac{L_{PIL}}{gA_{PIL}} \right] \ddot{W}^{**} + \frac{R_{IL}}{\rho} \dot{W}^{**2} = P_{IPD(t)} - P_{PI(t)} \qquad (27)$$

$$\ddot{V}_i' + 2\xi \omega_i' \dot{V}_i' + \omega_i'^2 V_i' = a_{1i}' \; IPD(t) - a_{ni}' P_{PI(t)}$$

$$\dot{W}_{PIL(t)} = \dot{W}^{**} + \sum_{i=2}^{n} a_{1i}' \dot{V}_i' \qquad (28)$$

$$\dot{W}_{PI(t)} = \dot{W}'^{**} + \sum_{i=2}^{n} a_{ni}' \dot{V}_i' \qquad (29)$$

J. Inducer Outlet Compliance and Main Pump Inlet Compliance

1. Inducer Outlet

$$P_{IPD} = (1/C_2) \; IP \int_0^t (W_{IP} + W_{IT} - W_{PIL}) \, dt \qquad (30)$$

2. Main Pump Inlet

$$\sigma_P = \frac{(NPSHP)(12)(2g)}{(N_P)^2 (RP)^2 (1 + \varphi_p^2)}$$

$$(1/C)_p = f(\sigma_p)$$

$$P_{PI} = (1/C)_P \int_0^t (W_{PI} - W_P) \, dt \qquad (31)$$

K. Main Pump

1. Head

$$\varphi_P = \dot{W}_P/(\rho)\ (N_P)\ (A_P)\ (R_P)$$

$$\psi_P = f(\varphi_P) \tag{32}$$

$$\overline{\Delta P_P} = \psi_P(\rho)\ (N_P)^2\ (R^2)/g \tag{33}$$

Cavitation Correction

$$\left(\frac{\Delta P}{\overline{\Delta P}}\right)_P = f(NPSH_P, \varphi_P)$$

$$NPSH_P = (P_{PI} - P_{VAP})/(12)\ (\rho) \tag{34}$$

$$\Delta P_P = \left(\frac{\Delta P}{\overline{\Delta P}}\right)_P\ \overline{\Delta P_P} \tag{35}$$

$$P_{PD} = P_{PI} + \Delta P_P \tag{36}$$

2. Torque

$$\chi_P = f(\varphi_P)$$

$$T_P = \chi_P\ (\rho)\ (N_P)^2\ (R_P)^3\ (A_P)/g \tag{37}$$

$$T_P = T_P \left(\frac{\Delta P}{\overline{\Delta P}}\right)_P \tag{38}$$

L. Facility Drive System Torque

1. For Program Checkout

$$N_P = f(TIME) \qquad \text{(Replaces Eq. 39)}$$

M. Main Pump Speed

$$N_P = N_P + 1/I_{(DS + P)}\ (T_{DS} - T_P)\ \Delta t \tag{39}$$

N. Pump Discharge Line

1. Time Delay Equations

$$\tau_{PDL} = L_{PDL}/a_{PDL}$$

$$\gamma_{PDL} = a_{PDL}/gA_{PDL}$$

$$P_{PD(t)} = P_{VI(t - \tau_{PDL})} + \gamma_{PDL} \dot{W}_{PDL(t)} - \dot{W}_{V(t - \tau_{PDL})} + \frac{R_{PDLI}}{\rho} \left[W_{DL(t)}\right]^2 + \frac{R_{PDL0}}{\rho} \left[\dot{W}_{V(t - \tau_{PDL})}\right]^2 \quad (40)$$

$$P_{VI(t)} = P_{PD(t - \tau_{PDL})} - \gamma_{PDL} \left[\dot{W}_{V(t)} - \dot{W}_{DL(t - \tau_{PDL})}\right]^2 - \frac{R_{PDL0}}{\rho} \left[W_{V(t)^2}\right] - \frac{R_{PDLI}}{\rho} \left[W_{DL(t - \tau_{PDL})}\right]^2 \quad (41)$$

2. Modal Equations

$$\ddot{V}_i + 2\xi \omega_i \dot{V}_i + \omega_i^2 V_i = a_{1i} P_{PD} - a_{Vi} \Delta P_V - a_{ni} (P_T - L_T \rho)$$

$$\left[\frac{L^*_{DL}}{gA_{DL}}\right] \dot{W}^*_{DL} + \frac{RV}{\rho} (\dot{W}^*_{DL})^2 = (P_{PD} - P_T + L_T \rho) \quad (42)$$

$$\dot{W}_{DL} = \dot{W}^*_{DL} + \sum_{i=2}^{n} a_{1i} \ddot{V}_i \quad (43)$$

$$\dot{W}_V = \dot{W}^*_{DL} + \sum_{i=2}^{n} a_{Vi} \dot{V}_i \quad (44)$$

O. Discharge Valve

$$P_{VI} - P_{VO} = \frac{R_V}{\rho} \left[\dot{W}_{V(t)}\right]^2 + \frac{L_V}{\Delta t} \left[\dot{W}_{V(t)} - \dot{W}_{V(t - \Delta t)}\right] \tag{45}$$

or, for Analog Program

$$\Delta P_V = \frac{R_V}{\rho} \dot{W}_{V(t)}^2$$

$$R_V = f(X_V)$$

P. Return Line

1. Time Delay Equations

$$\tau_{RL} = L_{RL}/a_{RL}$$

$$\gamma_{RL} = a_{RL}/gA_{RL}$$

$$P_{VO(t)} = P_T + \gamma_{RL} \left(\dot{W}_{V(t)} - \dot{W}_{T(t - \tau_{RL})}\right) + \frac{R_{RLI}}{\rho} \left(W_{V(t)}\right)^2 +$$

$$\frac{R_{RLO}}{\rho} \left(\dot{W}_{T(t - \tau_{RL})}\right)^2 + L_T \rho \tag{46}$$

$$P_T = P_{VO(t - \tau_{RL})} - \gamma_{RL} \left(\dot{W}_{T(t)} - \dot{W}_{V(t - \tau_{RL})}\right) -$$

$$- \frac{R_{RLO}}{\rho} \left(\dot{W}_{T(t)}\right)^2 - \frac{R_{RLI}}{\rho} \left(\dot{W}_{V(t - \tau_{RL})}\right)^2 - L_T \rho \tag{47}$$

2. Modal Equations

$$\dot{W}_T = \dot{W}^*_{DL} + \sum_{i=2}^{n} a_{ni} V_i \tag{48}$$

MODEL NOMENCLATURE

Symbol	Description
A1	Time delay line junction constant
A2	Time delay line junction constant
AIP	Normalizing area for inducer pump
ALPHIP	Inducer pump cavitation curve-fit coefficient
ALPHAP	Main pump cavitation curve-fit coefficient
AP	Normalizing area for main pump
CHIMP	Main pump torque parameter
CHIP	Inducer pump torque parameter
COMPPI	Main pump inlet compliance
DENPHI	Denominator of inducer pump flow coefficient
DNPHIP	Denominator of main pump flow coefficient
DPFV	Facility valve pressure drop
DPIT	Inducer turbine pressure drop
DPPI	Main pump inlet pressure derivative
DSP	Main pump speed derivative
DSPIP	Inducer pump speed derivative
DWIT	Inducer turbine flow derivative
DWPD	Main pump flow derivative
DXCAV	Inducer pump effective NPSH/$(\text{speed})^2$
DXCAPV	Main pump effective NPSH/$(\text{speed})^2$
GAMDL	Time delay line characteristic, main
GAMFL	Time delay line characteristic, facility return line
GAMIL	Time delay line characteristic, tank-to-interface line
GAMIP	Time delay line characteristic, inducer inlet line
IDP	Inducer pump, cavitating pressure rise
IDPBAR	Inducer pump noncavitating pressure rise
IITP	Reciprocal of inducer rotating moment of inertia
IMP	Reciprocal of main pump rotating moment of inertia
IPICOM	Inducer pump inlet compliance
IPINER	Inducer pump fluid inertia
IPOCOM	Inducer pump outlet compliance
IPPRAT	Inducer pump cavitating to noncavitating pressure ratio

Symbol	Description
ITFLCO	Inducer turbine flow coefficient
LDL	Main pump discharge line fluid inertia
LT	Fluid height in tank
LV	Discharge valve fluid inertia
NPSHIP	Inducer pump net positive suction head
NPSHP	Main pump
PDP	Main pump cavitating pressure rise
PDPBAR	Main pump noncavitating pressure rise
PFUI	Main pump discharge valve inlet pressure
PFVD	Main pump discharge valve outlet pressure
PHIIP	Inducer pump flow coefficient
PHIP	Main pump flow coefficient
PILD	Inducer inlet line interface pressure
PILU	Tube bundle outlet pressure
PIPIN	Inducer pump inlet pressure
PIPOUT	Inducer pump outlet pressure
PITI	Inducer turbine inlet pressure
PPD	Main pump outlet pressure
PPLI	Turbine tapoff junction pressure
PPI	Main pump inlet pressure
PPRAT	Main pump cavitating to noncavitating pressure ratio
PSIIP	Inducer pump head coefficient
PSIP	Main pump head coefficient
PT	Tank pressure
PVAP	Vapor pressure
PWC	Water cooler pressure
RDL	Discharge line resistance
RITO	Fluid density
RILI	Inducer inlet line resistance
RILU	Interface line resistance
RIP	Inducer pump normalizing radius
RIT	Inducer turbine flow resistance
RITV	Inducer turbine valve resistance
RP	Main pump normalizing radius

Symbol	Description
RPMIP	Inducer pump speed
RPMP	Main pump speed
RTB	Tube bundle resistance
RV	Discharge valve resistance
SIGIP	Inducer pump cavitation parameter
SIGP	Main pump cavitation parameter
SIP	Inducer pump speed
SIPO	Inducer pump speed initial value
SP	Main pump speed
TDPIT	Inducer turbine torque to ΔP ratio
TORQF	Main pump input torque
TORQIP	Inducer pump torque
TORQIT	Inducer turbine torque
TORQP	Main pump torque
$\dot{V}$	Modal velocities
WCLI	Coupling line inlet flowrate
WCLD	Coupling line outlet flowrate
WFV	Discharge valve flowrate
WILD	Inlet interface flowrate
WILU	Tube bundle outlet lfowrate
WIP	Inducer pump flowrate
WIPLD	Inducer inlet line flowrate
WIT	Inducer turbine flowrate
WP	Main pump flowrate
WPD	Pump discharge flowrate
WT	Tank return flowrate
WWC	Water cooler flowrate
XDV	Discharge line valve position
XITV	Inducer turbine valve position
Y1 through Y12	Time delay line delayed values

DIGITAL MODEL PROGRAM LISTINGS

****CONTINUOUS SYSTEM MODELING PRCGRAM****

PROBLEM INPUT STATEMENTS

```
*      CONTROL TIMES AND OUTPUT                                                    CT-00010
TIMER FINTIM=4.0,PRDEL=0.02,DELT=0.0005,OUTDEL=0.08                                CT-00020
PRINT PILU,WILU,PILD,WILD,NPSHIP,PHIP,PIPIN,WFV1,WIPLD,WIP,WIT,WP,...              CT-00050
      PIPOUT,RPMIP,NPSHP,PITI,RPMP,PPD,PFVI,PFVO,WT,PPLI,WPD,...                   CT-00060
      TORQIT,TORQIP,PHIIP,SIGIP,IPICCM,IPINER,IPCCCM,IDPBAR,...                    CT-00061
      IPPRAT,PDPBAR,PPRAT,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8,Y9,Y10,PWC,WWC                   CT-00062
TITLE PRE-INDUCER-PUMP TEST SYSTEM                                                 CT-00100
PRTPLT SIP(0.C,500.C),SP(0.0,1000.0),PIPOUT(0.0,100.0),PIPIN(0.0,25.0)             CT-00110
PRTPLT PPD(0.C,1000.0),WIP(0.0,500.0),WP(0.0,500.0),WIT(0.0,100.0)                 CT-00111
PRTPLT PITI(C.C,500.C)                                                             CT-00112
LABEL PRE-INDUCER-PUMP TEST SYSTEM - CLOSE COUPLING                                CT-00115
MACRO  Y1=SPEED1(NUM1,DEN1,S1,Y1MAX)                                               SPED1010
PROCED  Y1=SPEED1(NUM1,DEN1,S1,Y1MAX)                                              SPED1015
      IF(S1)2,2,1                                                                  SPED1020
    1 Y1=NUM1/(DEN1*S1**2)                                                         SPED1025
       Y1=AMIN1(Y1,Y1MAX)                                                          SPED1030
       GO TO 3                                                                     SPED1035
    2 Y1=Y1MAX                                                                     SPED1040
    3 CONTINUE                                                                     SPED1045
ENDPRO                                                                             SPED1050
ENDMAC                                                                             SPED1055
MACRO  Y=SPEED(NUM,DEN,S)                                                          SPEED010
PROCED  Y=SPEED(NUM,DEN,S)                                                         SPEED020
      IF(S)2,2,1                                                                   SPEED030
    1 Y=NUM/(DEN*S)                                                                SPEED040
      GO TO 3                                                                      SPEED050
    2 Y=0.C                                                                        SPEED060
    3 CONTINUE                                                                     SPEED070
ENDPRO                                                                             SPEED080
ENDMAC                                                                             SPEED090
*TANK AND INDUCER INLET LINES                                                      IND00010
MEMORY DLAY(200)                                                                   IND00015
PARAM PT=15.C,LT=0.0,RHO=0.0361,RILI=0.0,RILO=0.0,RIPO=0.0,RIPI=0.0,...            IND00021
      RTB=3.735E-06,GAMIL=2.04,GAMIP=1.61,TAU1=0.00158,TAU2=0.00538                IND00022
INIT                                                                               IND00030
      A1=GAMIP/GAMIL                                                               IND00035
      A2=1.0+A1                                                                    IND00040
DYNAM                                                                              IND00045
      WILU=IMPL(C.0,0.001,WILU1)                                                   IND00055
```

```
                RILI=(RILI+RTB)/RHO*WILL*ABS(WILU)                                  IND00060
                WILUI=(Y1+PT+LT*RHO-RILI-15.0)/GAMIL                                IND00065
                RILU=RILI/RHO*WILU*ABS(WILU)                                        IND00084
                PILU=PT+LT*RHO-RTB/RHO*WILL*ABS(WILU)                               IND00100
                WILD=(Y2-PILD+15.0)/GAMIL                                           IND00115
                PILD=(Y3+A1*Y2)/A2+15.C                                             IND00125
          *     INDUCER PUMP                                                        IND00160
          AFGEN FIG6=0.C,100.0,0.2,100.0                                            IND00165
          AFGEN FIG1=-2.0,14.65,C.C,C.338,C.025,0.309,0.04,0.285,0.05,0.265,...     IND00170
                0.06,0.237,0.065,0.218,0.07,0.195,0.075,0.168,0.085,0.106,...       IND00171
                C.095,C.C28,0.11,-0.C93,2.C,-15.29                                  IND00172
          AFGEN FIG6A=C.C,C.C225,0.2,0.0225                                         IND00180
           AFGEN FIG2=0.0,6.3E-7,0.062,6.55E-7,0.0665,6.72E-7,0.0707,7.1E-7,...     IND00190
                0.074,7.6E-7,0.1,16.3E-7                                            IND00191
          AFGEN FIG6B=C.C,100.C,C.2,100.C                                           IND00200
          AFGEN FIG3=0.0,0.017C,0.0115,0.01842,0.025,0.01939,0.035,0.0197,0.05,...  IND00210
                C.0197,C.07,0.C189,0.095,0.C1685,0.115,0.0143,0.13,0.01175,...      IND00211
                0.15,0.CC69E,C.165,0.0027,C.18,-0.00318,2.0,-0.699                  IND00212
          AFGEN TORQHD=C.0,0.C,3.0,12320.0,5.0,12320.0                              IND00220
          AFGEN RDV=0.C,100C.C,100.0,0.CC02437,200.0,0.0002437                      IND00230
          AFGEN ITV=C.C,10C0.0,100.0,0.0005E8,200.0,0.000588                        IND00240
          PARAM SIP=0.C,RIP=4.E75,AIP=64.25,WIT=0.0,SIPD=0.0,...                    IND00250
                PVAP=0.5,WIP=C.0,PIPD=15.0,IPIIC=15.0,WP=0.0....                    IND00251
                IPOIC=15.0,IPWIC=0.0                                                IND00252
                NPSHIP=AMAX1(C.3,(PIPIN-PVAP)/(12.0*RHO))                           IND00260
                DENPHI=RHO*RIP*AIP                                                  IND00265
                PHIIP=SPEED(WIP,DENPHI,SIP)                                         IND00270

GENERATED STRUCTURE STATEMENTS
    PROCED      PHIIP =SPEED(     WIP   ,     DENPHI,     SIP   )
    IF(   SIP   )     30004 ,     30004 ,     30003
    30003       PHIIP =     WIP   /(    DENPHI*     SIP   )
    GO TO 30005
    30004       PHIIP =C.C
    30005  CONTINUE
    ENDPRC

                SIGNUM=NPSHIP*9273.E                                                IND00275
                SIGDEN=(1.C+PHIIP**2)*RIP**2                                        IND00280
                SIGIP=SPEED1(SIGNUM,SIGDEN,SIP,0.1)                                 IND00285

GENERATED STRUCTURE STATEMENTS
    PROCED      SIGIP =SPEED1(    SIGNUM,     SIGDEN,     SIP   ,     0.1   )
```

```
      IF(   SIP    )     30007 ,     30007 ,     30006
30006         SIGIP =     SIGNUM/(    SIGDEN*     SIP    **2)
      SIGIP =AMIN1(      SIGIP ,     0.1    )
      GO TO 30008
30007         SIGIP =     0.1
30008   CONTINUE
      ENDPRO
```

```
                IPICOM=AFGEN(FIG6,SIGIP)                                        IND00290
                IPINER=AFGEN(FIG6A,SIGIP)                                       IND00295
                IPOCOM=AFGEN(FIG6B,SIGIP)                                       IND00300
                PSIIP=AFGEN(FIG1,PHIIP)                                         IND00305
                IDPBAR=PSIIP*RHO*(SIP*RIP)**2/386.4                             IND00310
                ALPHIP=AFGEN(FIG2,PHIIP)                                        IND00315
                DXCAV1=SPEED1(NPSHIP,1,SIP,1.0E+5)                              IND00320
```

```
GENERATED STRUCTURE STATEMENTS
      PROCED        DXCAV1=SPEED1(     NPSHIP,     1      ,     SIP    ,     1.0E+5)
      IF(   SIP    )     30010 ,     30010 ,     30009
30009         DXCAV1=     NPSHIP/(    1      *     SIP    **2)
      DXCAV1=AMIN1(      DXCAV1,     1.0E+5)
      GO TO 30011
30010         DXCAV1=     1.0E+5
30011   CONTINUE
      ENDPRO
```

```
                DXCAV=AMAX1(6.36E-7,DXCAV1-0.002545*PHIIP**2)                   IND00325
                IPPRAT=AMAX1(0.1,1.0-ALPHIP/DXCAV)                              IND00330
                IDP=IDPBAR*IPPRAT                                               IND00335
                WIPLD=(Y4-PIPIN+15.0)/GAMIP                                     IND00360
                IICOMW=IPICOM*(WIPLD-WIP)                                       IND00385
                PIPIN=INTGRL(IPIIC,IICOMW)                                      IND00390
                IOCOMW=IPOCOM*(WIP+WIT-WP)                                      IND00395
                PIPOUT=INTGRL(IPOIC,IOCOMW)                                     IND00400
                IPDW=(IDP+PIPIN-PIPOUT)/IPINER                                  IND00405
                WIP=INTGRL(IPWIC,IPDW)                                          IND00410
                CHIP=AFGEN(FIG3,PHIIP)                                          IND00415
                TORQIP=CHIP*RHO*SIP**2*RIP**3*AIP*IPPRAT/386.4                  IND00420
                RPMIP=SIP*9.5493                                                IND00425
            *   INDUCER TURBINE                                                 TURB0010
            PARAM IITP=4.16,WITC=0.0,LITL=0.1344,XITV=100.0                     TURB0015
            AFGEN FIG5=0.0,9.4,1.079,8.0548,1.3488,7.7544,1.7984,7.2755,2.6976,... TURB0020
                  6.3885,3.5968,5.5806,5.3952,4.1437,5.9947,3.7053,6.744,3.1791,... TURB0021
```

```
      7.7074,2.5314,8.9920,1.7047,10.79,0.58773                          TURB0022
AFGEN ITR=0.0,0.0732,1.80,0.080345,3.5968,0.08581,5.9947,0.091212,...    TURB0025
      7.7074,0.09375,10.79,0.09555                                       TURB0026
      RITV=AFGEN(ITV,XITV)                                               TURB0035
      RIT=AFGEN(ITR,ITFLCO)                                              TURB0039
      DPIT=RIT*WIT*ABS(WIT)                                              TURB0040
      PITI=PIPOUT+DPIT                                                   TURB0045
      DWIT=(PPLI-PIPOUT-(RITV/RHO+RIT)*WIT*ABS(WIT))/LITL                TURB0050
      WIT=INTGRL(WITO,DWIT)                                              TURB0055
      TDPIT=AFGEN(FIG5,ITFLCO)                                           TURB0060
      TORQIT=TDPIT*DPIT                                                  TURB0065
      DSPIP=(TORQIT-TORQIP)*IITP                                         TURB0070
      SIP=INTGRL(SIPO,DSPIP)                                             TURB0075
      SIP=AMAX1(0.0,SIP)                                                 TURB0080

****OUTPUT NAME NOT UNIQUE ** WARNING ONLY****


****INPUT NAME SAME AS OUTPUT NAME**WARNING ONLY****

PROCED ITFLCO=FLCO(SIP,WIT)                                              TURB0085
       IF(WIT)10,20,10                                                   TURB0090
   10  ITFLCO=SIP/WIT                                                    TURB0095
       GO TO 25                                                          TURB0100
   20  ITFLCO=0.0                                                        TURB0105
   25  CONTINUE                                                          TURB0110
ENDPRO                                                                   TURB0115
*      MAIN PUMP                                                         PUMP0010
PARAM  AP=22.9,RP=5.1,SP=0.0,IMP=1.0                                     PUMP0020
AFGEN  FIG9=-4.0,0.2,0.0,0.029,0.024,0.0425,0.0375,0.047,0.0505,...      PUMP0025
       0.0502,0.0885,0.057,0.105,0.0607,0.113,0.0655,0.1203,0.0728,...   PUMP0026
       0.16,0.135                                                        PUMP0027
AFGEN  FIG7=-4.0,48.86,0.0,0.465,0.012,0.52,0.03,0.545,0.043,0.545,...   PUMP0030
       0.062,0.536,0.089,0.498,0.107,0.46,0.16,0.332,0.3803,-0.2         PUMP0031
AFGEN  FIG8=0.0,8.06E-07,0.03,7.4E-07,0.05,6.74E-07,0.07,5.96E-07,...    PUMP0035
       0.081,5.32E-07,0.082,5.3E-07,0.0843,5.32E-07,0.10,6.1E-07,...     PUMP0036
       0.11,6.5E-07,0.12,6.82E-07,0.14,7.44E-07                          PUMP0037
PARAM  RDL=0.00488,RDL=2.235E-6                                          PUMP0045
       NPSHP=AMAX1(0.3,(PIPOUT-PVAP)/(12.0*RHO))                         PUMP0055
       DNPHIP=RHO*RP*A[redacted]                                         PUMP0060
       PHIP=SPEED(WP,DNPHIP,SP)                                          PUMP0065
```

```
GENERATED STRUCTURE STATEMENTS
    PROCED      PHIP  =SPEED(     WP    ,     DNPHIP,     SP    )
    IF(   SP    )     30013 ,     30013 ,     30012
    30012       PHIP  =     WP    /(    DNPHIP*     SP    )
    GO TO 30014
    30013       PHIP  =0.0
    30014  CONTINUE
    ENDPRO
```

```
            PSIP=AFGEN(FIG7,PHIP)                                                    PUMP0070
            PDPBAR=PSIP*RHO*(SP*RP)**2/386.4                                         PUMP0075
            ALPHAP=AFGEN(FIG8,PHIP)                                                  PUMP0080
            DXCAVP=SPEED1(NPSHP,1,SP,1.0E+5)                                         PUMP0085
```

```
GENERATED STRUCTURE STATEMENTS
    PROCED      DXCAVP=SPEED1(    NPSHP ,     1     ,     SP    ,     1.0E+5)
    IF(   SP    )     30016 ,     30016 ,     30015
    30015       DXCAVP=     NPSHP /(    1     *     SP    **2)
    DXCAVP=AMIN1(     DXCAVP,     1.0E+5)
    GO TO 30017
    30016       DXCAVP=     1.0E+5
    30017  CONTINUE
    ENDPRO
```

```
            DCAVP=AMAX1(5.3E-07,DXCAVP-0.00122*PHIP**2)                              PUMP0090
            PPRAT=AMAX1(0.1,1.0-ALPHAP/DCAVP)                                        PUMP0095
            PDP=PDPBAR*PPRAT                                                         PUMP0100
            PPD=PIPOUT+PDP                                                           PUMP0105
            DWPD=(PPD-PPL1-RDL/RHO*WP*ABS(WP))/LDL                                   PUMP0107
            WP=INTGRL(0.0,DWPD)                                                      PUMP0108
            RPMP=SP*9.5493                                                           PUMP0110
            TORQF=AFGEN(TORQFD,TIME)                                                 PUMP0120
            CHIMP=AFGEN(FIG9,PHIP)                                                   PUMP0130
            TORQP=CHIMP*RHO*SP**2*RP**3*AP*PPRAT/386.4                               PUMP0140
            DSP=IMP*(TORQF-TORQP)                                                    PUMP0150
            SP=INTGRL(0.0,DSP)                                                       PUMP0160
        *   PUMP DISCHARGE AND FACILITY LINE                                         RETL0010
        PARAM GAMDL=4.51,RDLI=0.0,RDLO=0.0,TAU3=0.0019,TAU4=0.039,...                RETL0020
            GAMFL=2.065,RFLI=0.0,RFLO=0.0,XDV=100.0,LV=0.00416,TAU5=0.0455           RETL0025
            WPD=WP-WIT                                                               RETL0090
            PPLI=Y5+GAMDL*WPD+15.0                                                   RETL0110
            RV=AFGEN(RDV,XDV)                                                        RETL0125
```

```
            PFVI=Y6-GAMDL*WFV1+15.0                                          RETL0165
            PFVO=Y7+GAMFL*WFV1+15.0                                          RETL0185
            WT=(Y10-LT*RHO)/GAMFL                                            RETL0210
            ICFVW=(PFVI-PFVO-RV/RHO*WFV1*ABS(WFV1))/LV                       RETL0230
            WFV1=INTGRL(0.0,ICFVW)                                           RETL0240
            WWC=(Y8-Y9)/(2*GAMFL)                                            RETL0250
            PWC=Y8-GAMFL*WWC+PT                                              RETL0260
        NOSORT                                                               TDV00010
            IF(KEEP)100,100,50                                               TDV00015
         50 TDPPD=PFVI-GAMDL*WFV1+RDLO/RHO*WFV1*ABS(WFV1)-PT                 TDV00020
            Y5=DLAY(4,TAU3,TDPPD)                                            TDV00030
            TDPVI=PPLI+GAMDL*WPD-RDLI/RHO*WPD*ABS(WPD)-PT                    TDV00040
            Y6=DLAY(4,TAU3,TDPVI)                                            TDV00050
            TDPVO=PWC-GAMFL*WWC-PT                                           TDV00060
            Y7=DLAY(76,TAU4,TDPVO)                                           TDV00070
            TDTW=PWC+GAMFL*WWC-PT                                            TDV00080
            Y10=DLAY(91,TAU5,TDTW)                                           TDV00085
            TDWC=PFVO+GAMFL*WFV1-PT                                          TDV00089
            Y8=DLAY(76,TAU4,TDWC)                                            TDV00090
            TDTWC=-GAMFL*WT                                                  TDV00095
            Y9=DLAY(91,TAU5,TDTWC)                                           TDV00096
            TDWIL=-PILO+GAMIL*WILO-RILO/RHO*WILO*ABS(WILO)+15.0              TDV00100
            Y1=DLAY(4,TAU1,TDWIL)                                            TDV00110
            TDWOL=PILO+GAMIL*WILO-RILI/RHO*WILO*ABS(WILO)-15.0               TDV00120
            Y2=DLAY(4,TAU1,TDWOL)                                            TDV00130
            TDPOL=PIPIN-GAMIP*WIPLD+RIPO/RHO*WIPLD*ABS(WIPLD)-15.0           TDV00140
            Y3=DLAY(12,TAU2,TDPOL)                                           TDV00150
            TDWIP1=PILO+GAMIP*WILO-RIPO/RHO*WILO*ABS(WILO)-15.0              TDV00160
            Y4=DLAY(12,TAU2,TDWIP1)                                          TDV00170
        100 CONTINUE                                                         TDV00290
        SORT                                                                 TDV00350
        METHOD TRAPZ                                                         MISC0020
        END                                                                  MISC0030
        STOP                                                                 MISC0040
```

```
OUTPUT VARIABLE SEQUENCE
A1      A2      WIPLD   SIP     DENPHI  PHIIP   SIGDEN  NPSHIP  SIGNUM  SIGIP
IPICOM  IICOMW  PIPIN   IPOCOM  IOCOMW  PIPOUT  IPINER  DXCAV1  DXCAV   ALPHIP
IPPRAT  PSIIP   IDPBAR  IDP     IPDW    WIP     ITFLCC  RIT     RITV    WPD
PPLI    DWIT    WIT     CHIP    TORQIP  DPIT    TDPIT   TORQIT  DSPIP   SIP
DNPHIP  PHIP    NPSHP   DXCAVP  DCAVP   ALPHAP  PPRAT   PSIP    PDPBAR  PDP
PPD     DWPD    WP      CHIMP   TORQP   TORQP   DSP     SP      RV      PFVO
PFVI    ICFVW   WFV1    ZZCOC1  RIL1    WILO1   WILO    RILO    PILO    PILD
```

```
WILD    RPMIP   PITI    RPMP    WT      WWC     PWC     ZZ0013  TDPPD   Y5
TDPVI   Y6      TDPVO   Y7      TDTW    Y10     TDWC    Y8      TDTWC   Y9
TDWIL   Y1      TDWCL   Y2      TDPDL   Y3      TDWIPI  Y4

PARAMETERS NOT INPUT OR OUTPUTS NOT AVAILABLE TO SORT SECTION***SET TO ZERO***
Y1      Y2      Y3      Y4      Y5      Y6      Y7      Y10
Y8      Y9

 OUTPUTS     INPUTS    PARAMS  INTEGS + MEM BLKS  FORTRAN  DATA CDS
104(500)  161(1400)  73(400)   8+ 10= 18(300)  130(600)     49
```

```
            ****CONTINUOUS SYSTEM MODELING PROGRAM****

      ***PROBLEM INPUT STATEMENTS***

*      CONTROL TIMES AND OUTPUT                                                CT-00010
TIMER FINTIM=4.0,PRDEL=0.02,DELT=0.0005,OUTDEL=0.08                            CT-00020
PRINT PILU,WILU,PILD,WILD,NPSHIP,PHIP,PIPIN,WEV1,WIPLD,WIP,WIT,WP,...          CT-00050
      PIPOUT,RPMIP,NPSHP,PITI,RPMP,PPD,PEVI,PEVC,WT,PPLI,WPD,...               CT-00060
      TORQIT,TORQIP,PHIIP,SIGIP,IPICCM,IPINER,IPOCCM,IDPBAR,...                CT-00061
      IPPRAT,PDPBAR,PPRAT,PWC,WWC,PPI,WCLI,WCLC                                CT-00062
TITLE PRE-INDUCER-PUMP TEST SYSTEM-REMOTE COUPLING                             CT-00100
PRTPLT SIP(0.0,500.0),SP(0.0,1000.0),PIPOUT(0.0,100.0),PIPIN(0.0,25.0)         CT-00110
PRTPLT PPD(0.0,1000.0),WIP(0.0,500.0),WP(0.0,500.0),WIT(0.0,100.0)             CT-00111
PRTPLT PITI(0.0,500.0),PPI(0.0,100.0)                                          CT-00112
LABEL PRE-INDUCER-PUMP TEST SYSTEM-REMOTE COUPLING                             CT-00115
MACRO  Y1=SPEED1(NUM1,DEN1,S1,Y1MAX)                                           SPED1010
PROCED  Y1=SPEED1(NUM1,DEN1,S1,Y1MAX)                                          SPED1015
       IF(S1)2,2,1                                                             SPED1020
     1 Y1=NUM1/(DEN1*S1**2)                                                    SPED1025
       Y1=AMIN1(Y1,Y1MAX)                                                      SPED1030
       GO TO 3                                                                 SPED1035
     2 Y1=Y1MAX                                                                SPED1040
     3 CONTINUE                                                                SPED1045
ENDPRO                                                                         SPED1050
ENDMAC                                                                         SPED1055
MACRO  Y=SPEED(NUM,DEN,S)                                                      SPEED010
PROCED  Y=SPEED(NUM,DEN,S)                                                     SPEED020
       IF(S)2,2,1                                                              SPEED030
     1 Y=NUM/(DEN*S)                                                           SPEED040
       GO TO 3                                                                 SPEED050
     2 Y=0.0                                                                   SPEED060
     3 CONTINUE                                                                SPEED070
ENDPRO                                                                         SPEED080
ENDMAC                                                                         SPEED090
*TANK AND INDUCER INLET LINES                                                  IND00010
MEMORY DLAY(200)                                                               IND00015
PARAM PT=15.0,LT=0.0,RHO=0.0361,RILI=0.0,RILC=0.0,RIPO=0.0,RIPI=0.0,...        IND00021
      RTB=3.735E-06,GAMIL=2.04,GAMIP=1.61,TAU1=0.00158,TAU2=0.001714           IND00022
INIT                                                                           IND00030
      A1=GAMIP/GAMIL                                                           IND00035
      A2=1.0+A1                                                                IND00040
DYNAM                                                                          IND00045
      WILU=IMPL(0.0,0.001,WILLI)                                               IND00055
```

```
                RILI=(RILI+RTB)/RHO*WILL*ABS(WILU)                                  IND00060
                WILU1=(Y1+PT+LT*RHO-RIL1-15.0)/GAMIL                                IND00065
                RILU=RILI/RHO*WILU*ABS(WILU)                                        IND00084
                PILL=PT+LT*RHO-RTB/RHO*WILL*ABS(WILU)                               IND00100
                WILD=(Y2-PILD+15.0)/GAMIL                                           IND00115
                PILD=(Y3+A1*Y2)/A2+15.0                                             IND00125
          *     INDUCER PUMP                                                        IND00160
          AFGEN FIG6=0.0,100.0,0.2,100.0                                            IND00165
          AFGEN FIG1=-2.0,14.65,0.0,0.338,0.025,0.309,0.04,0.285,0.05,0.265,...     IND00170
                0.06,0.237,0.065,0.218,0.07,0.195,0.075,0.168,0.085,0.106,...       IND00171
                0.095,0.028,0.11,-0.093,2.0,-15.29                                  IND00172
          AFGEN FIG6A=0.0,0.0225,0.2,0.0225                                         IND00180
           AFGEN FIG2=0.0,6.3E-7,0.062,6.55E-7,0.0665,6.72E-7,0.0707,7.1E-7,...     IND00190
                0.074,7.6E-7,0.1,16.3E-7                                            IND00191
          AFGEN FIG6B=0.0,64.0,0.2,64.0                                             IND00200
          AFGEN FIG3=0.0,0.017C,0.0115,0.01842,0.025,0.01939,0.035,0.0197,0.05,...IND00210
                0.0197,0.07,0.0189,0.095,0.01685,0.115,0.0143,0.13,0.01175,...      IND00211
                0.15,0.00698,0.165,0.0027,0.18,-0.00318,2.0,-0.699                  IND00212
          AFGEN TORQFD=0.0,0.0,3.0,12320.0,5.0,12320.0                              IND00220
          AFGEN RDV=0.0,1000.0,100.0,0.0002437,200.0,0.0002437                      IND00230
          AFGEN ITV=0.0,1000.0,100.0,0.000588,200.0,0.000588                        IND00240
          PARAM SIP=0.0,RIP=4.875,AIP=64.25,WIT=0.0,SIPC=0.0,...                    IND00250
                PVAP=0.5,WIP=0.0,PIPD=15.0,IPIIC=15.0,WP=0.0,...                    IND00251
                IPOIC=15.0,IPWIC=0.0                                                IND00252
                NPSHIP=AMAX1(0.3,(PIPIN-PVAP)/(12.0*RHO))                           IND00260
                DENPHI=RHO*RIP*AIP                                                  IND00265
                PHIIP=SPEED(WIP,DENPHI,SIP)                                         IND00270

GENERATED STRUCTURE STATEMENTS
    PROCED      PHIIP =SPEED(     WIP   ,     DENPHI,     SIP   )
    IF(   SIP   )     30004 ,     30004 ,     30003
    30003       PHIIP =     WIP   /(    DENPHI*     SIP   )
    GO TO 30005
    30004       PHIIP =0.0
    30005  CONTINUE
    ENDPRO

                SIGNUM=NPSHIP*9273.6                                                IND00275
                SIGDEN=(1.0+PHIIP**2)*RIP**2                                        IND00280
                SIGIP=SPEED1(SIGNUM,SIGDEN,SIP,0.1)                                 IND00285

GENERATED STRUCTURE STATEMENTS
    PROCED      SIGIP =SPEED1(    SIGNUM,     SIGDEN,     SIP   ,     0.1   )
```

```
      IF(    SIP    )      30007 ,      30007 ,      30006
      30006         SIGIP =      SIGNUM/(     SIGDEN*      SIP    **2)
      SIGIP =AMIN1(      SIGIP ,      0.1    )
      GO TO 30008
      30007         SIGIP =      0.1
      30008  CONTINUE
      ENDPRO

                IPICOM=AFGEN(FIG6,SIGIP)                                          INDC0290
                IPINER=AFGEN(FIG6A,SIGIP)                                         INDC0295
                IPOCOM=AFGEN(FIG6B,SIGIP)                                         INDC0300
                PSIIP=AFGEN(FIG1,PHIIP)                                           INDC0305
                IDPBAR=PSIIP*RHO*(SIP*RIP)**2/386.4                               INDC0310
                ALPHIP=AFGEN(FIG2,PHIIP)                                          INDC0315
                DXCAV1=SPEED1(NPSHIP,1.,SIP,1.0E+5)                               INDC0320

GENERATED STRUCTURE STATEMENTS
      PROCED        DXCAV1=SPEED1(     NPSHIP,      1      ,      SIP    ,      1.0E+5)
      IF(    SIP    )      30010 ,      30010 ,      30009
      30009         DXCAV1=      NPSHIP/(     1      *      SIP    **2)
      DXCAV1=AMIN1(      DXCAV1,      1.0E+5)
      GO TO 30011
      30010         DXCAV1=      1.0E+5
      30011  CONTINUE
      ENDPRO

                DXCAV=AMAX1(6.367E-7,DXCAV1-0.002545*PHIIP**2)                    INDC0325
                IPPRAT=AMAX1(0.1,1.0-ALPHIP/DXCAV)                                INDC0330
                IDP=IDPBAR*IPPRAT                                                 INDC0335
                WIPLD=(Y4-PIPIN+15.0)/GAMIP                                       INDC0360
                IICOMW=IPICOM*(WIPLD-WIP)                                         INDC0385
                PIPIN=INTGRL(IPIIC,IICOMW)                                        INDC0390
                IOCOMW=IPOCOM*(WIP+WIT-WCLI)                                      INDC0395
                PIPOUT=INTGRL(IPOIC,IOCOMW)                                       INDC0400
                IPDW=(IDP+PIPIN-PIPOUT)/IPINER                                    INDC0405
                WIP=INTGRL(IPWIC,IPDW)                                            INDC0410
                CHIP=AFGEN(FIG3,PHIIP)                                            INDC0415
                TORQIP=CHIP*RHO*SIP**2*RIP**3*AIP*IPPRAT/386.4                    INDC0420
                RPMIP=SIP*5.5493                                                  INDC0425
          *     INDUCER TURBINE                                                   TURB0010
          PARAM IITP=4.16,WITO=0.0,LITL=0.1344,XITV=100.0                         TURB0015
          AFCEN FIG5=0.0,9.4,1.079,8.0548,1.3488,7.7544,1.7984,7.2755,2.6976,...  TURB0020
                6.3885,3.5968,5.5806,5.3952,4.1437,5.9947,3.7053,6.744,3.1791,... TURB0021
```

```
            7.7074,2.5314,8.9920,1.7047,10.79,0.58773                          TURB0022
      AFGEN ITR=C.C,0.0732,1.8C,0.080345,3.5968,0.08581,5.9947,0.091212,...    TURB0025
            7.7074,0.09375,1C.79,0.09555                                       TURB0026
            RITV=AFGEN(ITV,XITV)                                               TURB0035
            RIT=AFGEN(ITR,ITFLCC)                                              TURB0039
            DPIT=RIT*WIT*ABS(WIT)                                              TURB0040
            PITI=PIPCUT+DPIT                                                   TURB0045
            DWIT=(PPLI-PIPCUT-(RITV/RHC+RIT)*WIT*ABS(WIT))/LITL                TURB0050
            WIT=INTGRL(WITC,DWIT)                                              TURB0055
            TDPIT=AFGEN(FIG5,ITFLCC)                                           TURB0060
            TORQIT=TDPIT*DPIT                                                  TURB0065
            DSPIP=(TCRQIT-TCRQIP)*IITP                                         TURB0070
            SIP=INTGRL(SIPC,DSPIP)                                             TURB0075
            SIP=AMAX1(C.C,SIP)                                                 TURB0080

****OUTPUT NAME NOT UNIQUE ** WARNING ONLY****


****INPUT NAME SAME AS OUTPUT NAME**WARNING ONLY****

      PROCED ITFLCO=FLCO(SIP,WIT)                                              TURB0085
            IF(WIT)1C,20,1C                                                    TURB0090
         1C ITFLCO=SIP/WIT                                                     TURB0095
            GO TO 25                                                           TURB0100
         2C ITFLCO=C.C                                                         TURB0105
         25 CONTINUE                                                           TURB0110
      ENDPRO                                                                   TURB0115
      PARAM GAMCL=1.61,TAU6=C.003665,ICPPI=15.0                                PCL00010
      AFGEN FIG1C=0.0,1.0,C.01,8.5,0.016,20.0,0.02,40.0,0.025,72.0,0.03,...    PCL00020
            120.C,0.035,200.C,0.04,340.0,0.045,460.0,0.2,460.0                 PCL00021
            WCLI=(Y12+PIPCUT-PT)/GAMCL                                         PCL00030
            WCLO=(Y11-PPI+PT)/GAMCL                                            PCL00040
            SIGNL=NPSHP*9273.6                                                 PCL00050
            SIGDE=(1.C+PHIP**2)*RP**2                                          PCL00060
            SIGP=SPEED1(SIGNL,SIGDE,SP,0.1)                                    PCL00070

GENERATED STRUCTURE STATEMENTS
    PROCED      SIGP  =SPEED1(    SIGNL ,     SIGDE ,     SP    ,     0.1   )
    IF(   SP    )     30013 ,     30013 ,     30012
    3CC12       SIGP  =     SIGNL /(    SIGDE *     SP    **2)
    SIGP  =AMIN1(     SIGP  ,     0.1   )
```

```
3C01S        DXCAVP=      1.0E+5
3C02C  CONTINUE
ENDPRO

            DCAVP=AMAX1(5.3E-07,DXCAVP-0.00122*PHIP**2.0)                    PUMP0090
            PPRAT=AMAX1(0.1,1.0-ALPHAP/DXCAVP)                               PUMP0095
            PDP=PDPBAR*PPRAT                                                 PUMP0100
            PPD=PPI+PDP                                                      PUMP0105
            DWPD=(PPD-PPLI-RDL/RHO*WP*ABS(WP))/LDL                           PUMP0107
            WP=INTGRL(0.0,DWPD)                                              PUMP0108
            RPMP=SP*9.5493                                                   PUMP0110
            TORQF=AFGEN(TORQFD,TIME)                                         PUMP0120
            CHIMP=AFGEN(FIG9,PHIP)                                           PUMP0130
            TORQP=CHIMP*RHO*SP**2*RP**3*AP*PPRAT/386.4                       PUMP0140
            DSP=IMP*(TORQF-TORQP)                                            PUMP0150
            SP=INTGRL(0.0,DSP)                                               PUMP0160
        *   PUMP DISCHARGE AND FACILITY LINE                                 RETL0010
        PARAM GAMDL=4.51,RDLI=0.0,RDLC=0.0,TAU3=0.0019,TAU4=0.039,...        RETL0020
            GAMFL=2.085,RFLI=0.0,RFLO=0.0,XDV=100.0,LV=0.00416,TAU5=0.0455   RETL0025
            WPD=WP-WIT                                                       RETL0090
            PPLI=Y5+GAMDL*WPD+15.0                                           RETL0110
            RV=AFGEN(RDV,XDV)                                                RETL0125
            PFVI=Y6-GAMDL*WFV1+15.0                                          RETL0165
            PFVO=Y7+GAMFL*WFV1+15.0                                          RETL0185
            WT=(Y10-LT*RHO)/GAMFL                                            RETL0210
            ICFVW=(PFVI-PFVO-RV/RHO*WFV1*ABS(WFV1))/LV                       RETL0230
            WFV1=INTGRL(0.0,ICFVW)                                           RETL0240
            WWC=(Y8-Y9)/(2*GAMFL)                                            RETL0250
            PWC=Y8-GAMFL*WWC+PT                                              RETL0260
        NOSORT                                                               TDV00010
            IF(KEEP)100,100,50                                               TDV00015
         50 TDPPD=PFVI-GAMDL*WFV1+RDLC/RHO*WFV1*ABS(WFV1)-PT                 TDV00020
            Y5=DLAY(4,TAU3,TDPPD)                                            TDV00030
            TDPVI=PPLI+GAMDL*WPD-RDLI/RHO*WPD*ABS(WPD)-PT                    TDV00040
            Y6=DLAY(4,TAU3,TDPVI)                                            TDV00050
            TDPVO=PWC-GAMFL*WWC-PT                                           TDV00060
            Y7=DLAY(78,TAU4,TDPVO)                                           TDV00070
            TDTW=PWC+GAMFL*WWC-PT                                            TDV00080
            Y10=DLAY(91,TAU5,TDTW)                                           TDV00085
            TDWC=PFVO+GAMFL*WFV1-PT                                          TDV00089
            Y8=DLAY(78,TAU4,TDWC)                                            TDV00090
            TDTWC=-GAMFL*WT                                                  TDV00095
            Y9=DLAY(91,TAU5,TDTWC)                                           TDV00096
```

```
      GO TO 3CC14
      3CC13        SIGP   =      C.1
      3CC14  CONTINUE
      ENDPRO

            COMPPI=AFGEN(FIG10,SIGP)                                          PCLC0080
            DPPI=COMPPI*(WCLC-WP)                                             PCLC0090
            PPI=INTGRL(ICPPI,DPPI)                                            PCLC0100
      *     MAIN PUMP                                                         PUMP0010
      PARAM AP=22.9,RP=5.1,SP=0.0,IMP=1.0                                     PUMP0020
      AFGEN FIG9=-4.0,0.2,C.C,0.029,0.024,0.0425,0.0375,0.047,0.0505,...      PUMP0025
            0.0502,C.0885,C.057,0.105,0.0607,0.113,0.0655,0.1203,0.0728,...   PUMP0026
            0.16,C.135                                                        PUMP0027
      AFGEN FIG7=-4.0,48.86,C.0,0.465,0.012,0.52,0.03,0.545,0.043,0.545,...   PUMP0030
            0.062,0.536,C.089,0.498,0.107,0.46,0.16,0.332,0.3803,-0.2         PUMP0031
      AFGEN FIG8=0.C,8.06E-C7,0.03,7.4E-07,0.05,6.74E-07,0.07,5.96E-07,...    PUMP0035
            0.081,5.32E-C7,0.082,5.3E-07,0.0843,5.32E-07,0.10,6.1E-C7,...     PUMP0036
            C.11,6.5E-C7,C.12,6.82E-07,0.14,7.44E-07                          PUMP0037
      PARAM LDL=C.CC488,RDL=2.235E-6                                          PUMP0045
            NPSHP=AMAX1(C.3,(PPI-PVAP)/(12.0*RHC))                            PUMP0055
            DNPHIP=RHO*RP*AP                                                  PUMP0060
            PHIP=SPEED(WP,DNPHIP,SP)                                          PUMP0065

GENERATED STRUCTURE STATEMENTS
    PROCED       PHIP  =SPEED(      WP    ,      DNPHIP,      SP    )
    IF(   SP     )      30016 ,     30016 ,     30015
    3CC15        PHIP  =      WP    /(    DNPHIP*      SP    )
    GO TO 3CC17
    3CC16        PHIP  =C.C
    3CC17  CONTINUE
    ENDPRO

            PSIP=AFGEN(FIG7,PHIP)                                             PUMP0070
            PDPBAR=PSIP*RHC*(SP*RP)**2/386.4                                  PUMP0075
            ALPHAP=AFGEN(FIG8,PHIP)                                           PUMP0080
            DXCAVP=SPEED1(NPSHP,1,SP,1.0E+5)                                  PUMP0085

GENERATED STRUCTURE STATEMENTS
    PROCED       DXCAVP=SPEED1(     NPSHP ,      1     ,      SP    ,      1.0E+5)
    IF(   SP     )      30019 ,     30019 ,     30018
    3CC18        DXCAVP=      NPSHP /(    1     *      SP    **2)
    DXCAVP=AMIN1(      DXCAVP,     1.0E+5)
    GO TO 3C02C
```

```
            TDWIL=-PILD+GAMIL*WILD-RILC/RHO*WILD*ABS(WILD)+15.0                TDVC0100
            Y1=DLAY(4,TAU1,TDWIL)                                             TDVC0110
            TDWDL=PILU+GAMIL*WILU-RILI/RHO*WILU*ABS(WILU)-15.0                TDVC0120
            Y2=DLAY(4,TAU1,TDWDL)                                             TDVC0130
            TDPDL=PIPIN-GAMIP*WIPLD+RIPC/RHO*WIPLD*ABS(WIPLD)-15.0            TDVC0140
            Y3=DLAY(4,TAU2,TDPDL)                                             TDVC0150
            TDWIPI=PILD+GAMIP*WILD-RIPC/RHO*WILD*ABS(WILD)-15.0               TDVC0160
            Y4=DLAY(4,TAU2,TDWIPI)                                            TDVC0170
            TDCLO=-PPI+GAMCL*WCLC+PT                                          TDVC0180
            Y12=DLAY(8,TAU6,TDCLC)                                            TDVC0190
            TDCLI=PIPOUT+GAMCL*WCLI-PT                                        TDVC0200
            Y11=DLAY(8,TAU6,TDCLI)                                            TDVC0210
          100 CONTINUE                                                        TDVC0290
        SORT                                                                  TDVC0350
        METHOD TRAPZ                                                          MISC0020
        END                                                                   MISC0030
        STOP                                                                  MISC0040
```

```
OUTPUT VARIABLE SEQUENCE
A1      A2      WIPLD   SIP     DENPHI  PHIIP   SIGDEN  NPSHIP  SIGNUM  SIGIP
IPICOM  IICOMW  PIPIN   WCLI    IPCCOM  ICCCMW  PIPOUT  IPINER  CXCAV1  DXCAV
ALPHIP  IPPRAT  PSIIP   IDPBAR  IDP     IPDW    WIP     ITELCC  RIT     RITV
WPD     PPLI    DWIT    WIT     CHIP    TORQIP  DPIT    TCPIT   TORQIT  DSPIP
SIP     WCLO    DNPHIP  PHIP    SIGDE   NPSHP   SIGNU   SIGP    COMPPI  DPPI
PPI     DXCAVP  ALPHAP  PPRAT   PSIP    PDPBAR  PDP     PPD     DWPC    WP
CHIMP   TORQP   TORQF   DSP     SP      RV      PFVC    PFVI    ICFVW   WFV1
ZZCC01  RIL1    WILU1   WILU    RILU    PILU    PILD    WILD    RPMIP   PITI
DCAVP   RPMP    WT      WWC     PWC     ZZ0014  TDPPD   Y5      TDPVI   Y6
TDPVO   Y7      TDTW    Y10     TDWC    Y8      TDTWC   Y9      TDWIL   Y1
TDWDL   Y2      TDPDL   Y3      TDWIPI  Y4      TDCLC   Y12     TDCLI   Y11

PARAMETERS NOT INPUT OR OUTPUTS NOT AVAILABLE TO SORT SECTION***SET TO ZERO***
Y1      Y2      Y3      Y4      Y12     Y11     Y5      Y6
Y7      Y10     Y8      Y9

 OUTPUTS    INPUTS   PARAMS  INTEGS + MEM BLKS  FORTRAN  DATA CDS
116(500)  177(1400)  79(400)   9+ 12= 21(300)  147(600)     52
```

COMPILER OPTIONS - NAME= MAIN,OPT=00,LINECNT=40,SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID

```
ISN 0002          FUNCTION DLAY(L,N,TD,XIN)                                  DELA0010
ISN 0003          DIMENSION KX(1),X(1)                                       DELA  20
ISN 0004          COMMON DDUM1(64),C(8000),NALARM,DDUM2(12),KPT1,DDUM3(405),KEEP
ISN 0005          COMMON DDUM4(1316),SYMB(1)
ISN 0006          EQUIVALENCE(C(1),TIME),(C(2),DELT),(X(1),KX(1),SYMB(1))    DELA  70
ISN 0007          K=L+6*(KPT1-1)                                             DELA  80
ISN 0008          IF(TIME-0.0000I)100C,1000,1010                             DELA0090
ISN 0009     1000 X(K-6)=TD/FLOAT(N)                                         DELA 100
ISN 0010          X(K-5)=X(K-6)                                              DELA 110
ISN 0011          KX(K-4)=0                                                  DELA 120
ISN 0012          KX(K-3)=K                                                  DELA 130
ISN 0013          KX(K-2)=N+N+2                                              DELA 140
ISN 0014          KX(K-1)=K+KX(K-2)-2                                        DELA 150
ISN 0015          X(K)=0.                                                    DELA 160
ISN 0016          X(K+1)=XIN                                                 DELA 170
ISN 0017          DLAY=0.0                                                   DELA0180
ISN 0018          GO TO 1210                                                 DELA 190
                C... TEST IF TIME FOR OUTPUT                                 DELA 200
ISN 0019     1010 TIMEX=TIME-TD+DELT                                         DELA0210
ISN 0020          IF(TIMEX+.5*DELT)1020,1030,1030                            DELA 220
ISN 0021     1020 DLAY=0.0                                                   DELA0230
ISN 0022          GO TO 1140                                                 DELA 240
ISN 0023     1030 IF(TIME-TD)1120,1040,1040                                  DELA0250
ISN 0024     1040 KEND=KX(K-1)-4                                             DELA0260
ISN 0025          INDEX=KX(K-3)                                              DELA 270
ISN 0026          IF(KX(K-4)-KX(K-2))1080,1080,1050                          DELA 280
ISN 0027     1050 IF(INDEX-KEND)106C,1080,1080                               DELA0290
ISN 0028     106C I2=INDEX+2                                                 DELA 300
ISN 0029          KEND1=KX(K-1)                                              DELA0305
ISN 0030          DO 1070 I=I2,KEND1,2                                       DELA0310
ISN 0031          IF(TIMEX-X(I))1130,1110,1070                               DELA 320
ISN 0032     107C CONTINUE                                                   DELA 330
ISN 0033     108C DO 1090 I=K,INDEX,2                                        DELA 340
ISN 0034          IF(TIMEX-X(I))1130,111C,1090                               DELA 350
ISN 0035     109C CONTINUE                                                   DELA 360
ISN 0036     1100 DLAY=XIN-TD*(XIN-X(I+1))/(TIME-X(I))                       DELA0370
ISN 0037          GO TO 1140                                                 DELA 380
ISN 0038     1110 DLAY=X(I+1)                                                DELA0390
ISN 0039          GO TO 1140                                                 DELA 400
```

```
ISN 0040      1120  DLAY=X(K+1)                                                    DELA0410
ISN 0041            GO TO 1140                                                     DELA 420
ISN 0042      1130  DLAY=X(I-1)+(X(I+1)-X(I-1))*(TIMEX-X(I-2))/(X(I)-X(I-2))      DELA0430
                C...  TEST IF TIME TO STORE INPUT                                  DELA 440
ISN 0043      1140  IF(KEEP)1210,1210,1150                                         DELA 450
ISN 0044      1150  IF(X(K-5)-TIME-0.5*DELT)1160,1160,1210                       DELA 460
ISN 0045      1160  KX(K-4)=KX(K-4)+2                                            DELA 470
ISN 0046            X(K-5)=X(K-5)+X(K-6)                                         DELA 480
ISN 0047            IF(X(K-5)-TIME)1170,1170,1180                                DELA 490
ISN 0048      1170  X(K-5)=TIME+X(K-6)                                           DELA 500
ISN 0049      1180  I=MOD(KX(K-4),KX(K-2))                                       DELA 510
ISN 0050            IF(I)1100,1190,1200                                          DELA 520
ISN 0051      1190  X(K)=X(INDEX)                                               DELA 530
ISN 0052            X(K+1)=X(INDEX+1)                                            DELA 540
ISN 0053            I=2                                                          DELA 550
ISN 0054            KX(K-4)=KX(K-4)+2                                            DELA 560
ISN 0055      1200  INDEX=I+K                                                    DELA 570
ISN 0056            KX(K-3)=INDEX                                                DELA 580
ISN 0057            X(INDEX)=TIME                                                DELA 590
ISN 0058            X(INDEX+1)=XIN                                               DELA 600
ISN 0059      1210  RETURN                                                       DELA 610
ISN 0060            END                                                          DELA 620
```

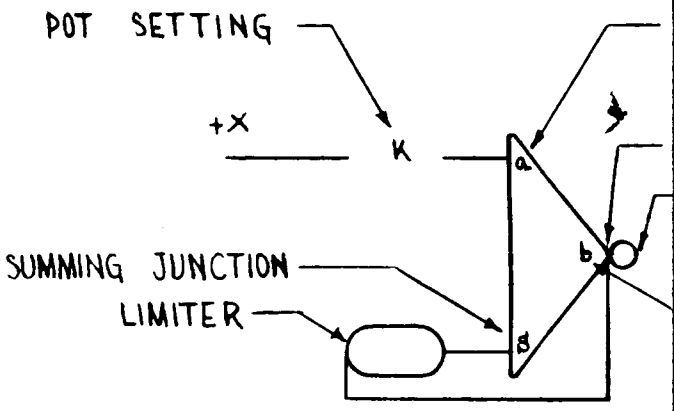
SAMPLE PRINTED OUTPUT

PRE-INDUCER-PUMP TEST SYSTEM-REMOTE COUPLING

TRAPZ INTEGRATION

TIME =	6.6667E-01	PILU =	1.3212E 01	WILU =	1.3145E 02	PILD =	1.1766E 01	WILD =	1.3146E 02		
		NPSHIP=	2.3147E 01	PHIP =	9.4499E-02	PIPIN =	1.0527E 01	WFV1 =	1.2495E 02		
		WIPLD =	1.3148E 02	WIP =	1.3161E 02	WIT =	3.1759E 01	WP =	1.5688E 02		
		PIPOUT=	4.2738E 00	RPMIP =	1.2869E 03	NPSHP =	2.3013E 00	PITI =	9.0048E 01		
		RPMP =	3.7600E 03	PPD =	1.7755E 02	PFVI =	1.7180E 02	PFVD =	6.4386E 01		
		WT =	1.2572E 02	PPLI =	1.7440E 02	WPD =	1.2512E 02	TORQIT=	2.6854E 02		
		TORQIP=	1.3943E 02	PHIIP =	8.6366E-02	SIGIP =	1.0000E-01	IPICOM=	1.0000E 02		
		IPINER=	2.2500E-02	IPOCOM=	6.4000E 01	IDPBAR=	3.8451E 00	IPPRAT=	9.9907E-01		
		PUPBAR=	1.8325E 02	PPRAT =	9.6075E-01	PWC =	4.0050E 01	WWC =	1.2599E 02		
		PPI =	1.4969E 00	WCLI =	1.6298E 02	WCLO =	1.6292E 02				
TIME =	6.9333E-01	PILU =	1.2871E 01	WILU =	1.4344E 02	PILD =	1.1435E 01	WILD =	1.4345E 02		
		NPSHIP=	2.2408E 01	PHIP =	9.7909E-02	PIPIN =	1.0207E 01	WFV1 =	1.3235E 02		
		WIPLD =	1.4346E 02	WIP =	1.4352E 02	WIT =	3.2612E 01	WP =	1.6512E 02		
		PIPOUT=	5.4670E 00	RPMIP =	1.4206E 03	NPSHP =	6.2652E 00	PITI =	9.5910E 01		
		RPMP =	3.8197E 03	PPD =	1.8667E 02	PFVI =	1.8126E 02	PFVD =	6.1048E 01		
		WT =	1.3257E 02	PPLI =	1.8354E 02	WPD =	1.3251E 02	TORQIT=	2.9322E 02		
		TORQIP=	1.7070E 02	PHIIP =	8.5322E-02	SIGIP =	1.0000E-01	IPICOM=	1.0000E 02		
		IPINER=	2.2500E-02	IPOCOM=	6.4000E 01	IDPBAR=	5.0852E 00	IPPRAT=	9.9885E-01		
		PUPBAR=	1.8631E 02	PPRAT =	9.8469E-01	PWC =	4.0432E 01	WWC =	1.3331E 02		
		PPI =	3.2141E 00	WCLI =	1.7492E 02	WCLO =	1.7466E 02				
TIME =	7.2000E-01	PILU =	1.2555E 01	WILU =	1.5373E 02	PILD =	1.1963E 01	WILD =	1.5369E 02		
		NPSHIP=	2.5348E 01	PHIP =	1.0123E-01	PIPIN =	1.1481E 01	WFV1 =	1.3938E 02		
		WIPLD =	1.5351E 02	WIP =	1.5141E 02	WIT =	3.3197E 01	WP =	1.7277E 02		
		PIPOUT=	1.8168E 01	RPMIP =	1.5469E 03	NPSHP =	2.0886E 01	PITI =	1.1189E 02		
		RPMP =	3.8657E 03	PPD =	1.9667E 02	PFVI =	1.9245E 02	PFVD =	5.9701E 01		
		WT =	1.4028E 02	PPLI =	1.9392E 02	WPD =	1.3957E 02	TORQIT=	3.1367E 02		
		TORQIP=	2.0491E 02	PHIIP =	8.2666E-02	SIGIP =	1.0000E-01	IPICOM=	1.0000E 02		
		IPINER=	2.2500E-02	IPOCOM=	6.4000E 01	IDPBAR=	7.0189E 00	IPPRAT=	9.9889E-01		
		PUPBAR=	1.8803E 02	PPRAT =	9.9518E-01	PWC =	4.0282E 01	WWC =	1.3978E 02		
		PPI =	9.5479E 00	WCLI =	1.7754E 02	WCLO =	1.7488E 02				
TIME =	7.4667E-01	PILU =	1.2691E 01	WILU =	1.4939E 02	PILD =	1.3206E 01	WILD =	1.4941E 02		
		NPSHIP=	3.0343E 01	PHIP =	1.0447E-01	PIPIN =	1.3645E 01	WFV1 =	1.4666E 02		
		WIPLD =	1.4950E 02	WIP =	1.5062E 02	WIT =	3.3392E 01	WP =	1.8041E 02		
		PIPOUT=	2.6913E 01	RPMIP =	1.6509E 03	NPSHP =	5.6718E 01	PITI =	1.2174E 02		
		RPMP =	3.9113E 03	PPD =	2.1443E 02	PFVI =	2.0846E 02	PFVD =	6.0922E 01		
		WT =	1.4754E 02	PPLI =	2.1098E 02	WPD =	1.4702E 02	TORQIT=	3.2558E 02		
		TORQIP=	2.3951E 02	PHIIP =	7.7051E-02	SIGIP =	1.0000E-01	IPICOM=	1.0000E 02		
		IPINER=	2.2500E-02	IPOCOM=	6.4000E 01	IDPBAR=	1.0304E 01	IPPRAT=	9.9914E-01		

SUMMER



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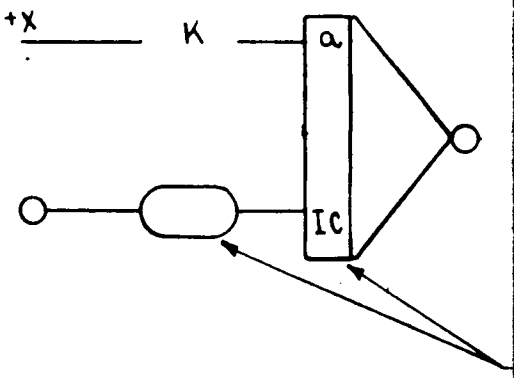

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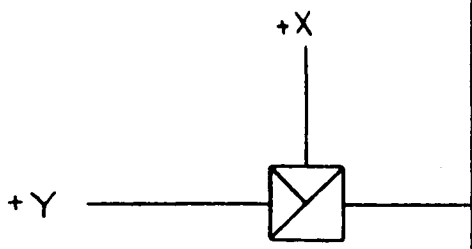

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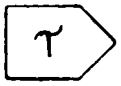


— TIME DELA

— TRUNK IN

FOLDOUT FRAME

INPUT RESISTOR { 1 = 1 MEGOHM
.1 = 0.1 MEGOHM

-KX

-+KX

FEED BACK
RESISTOR
0.1 MEGOHM IF NOT NOTED
10 DENOTES 1 MEGOHM
100 DENOTES 10 MEGOHMS

$+\int KX\,dt$
1 μf FEEDBACK
IF NOT NOTED

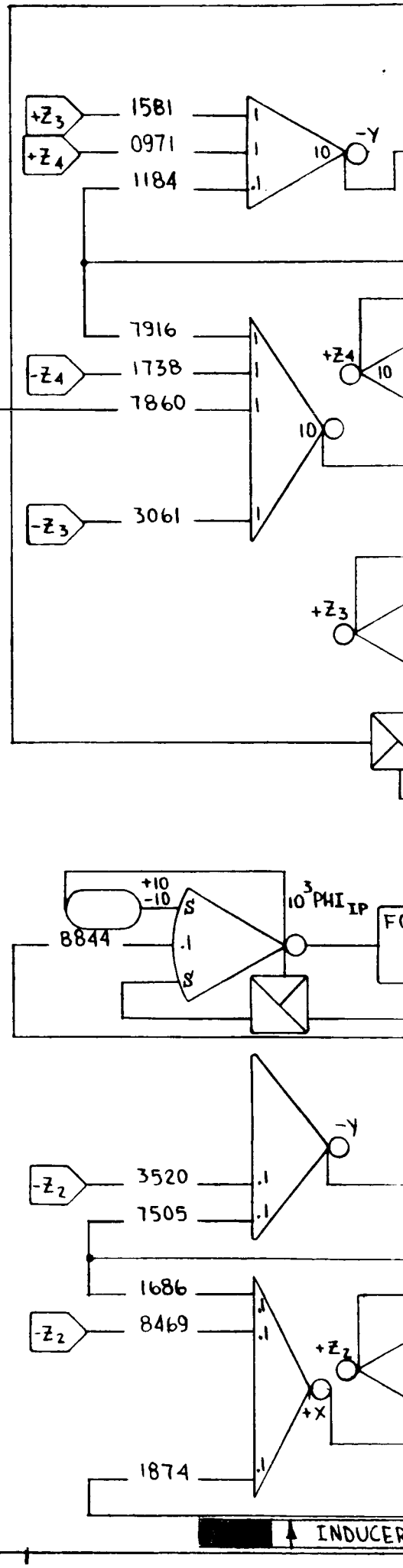
INITIAL CONDITION POT

+XY/100

SWITCH

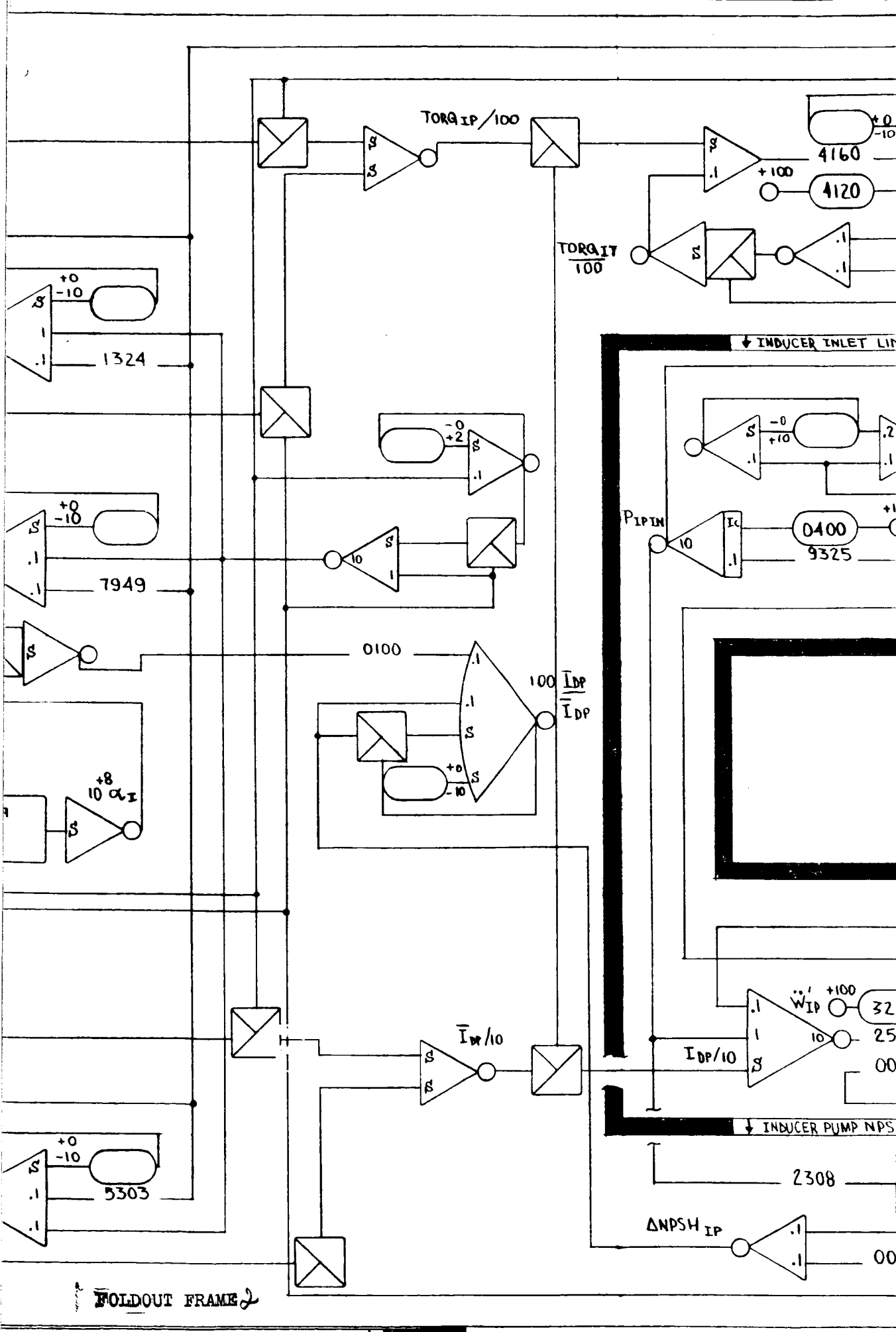
Y

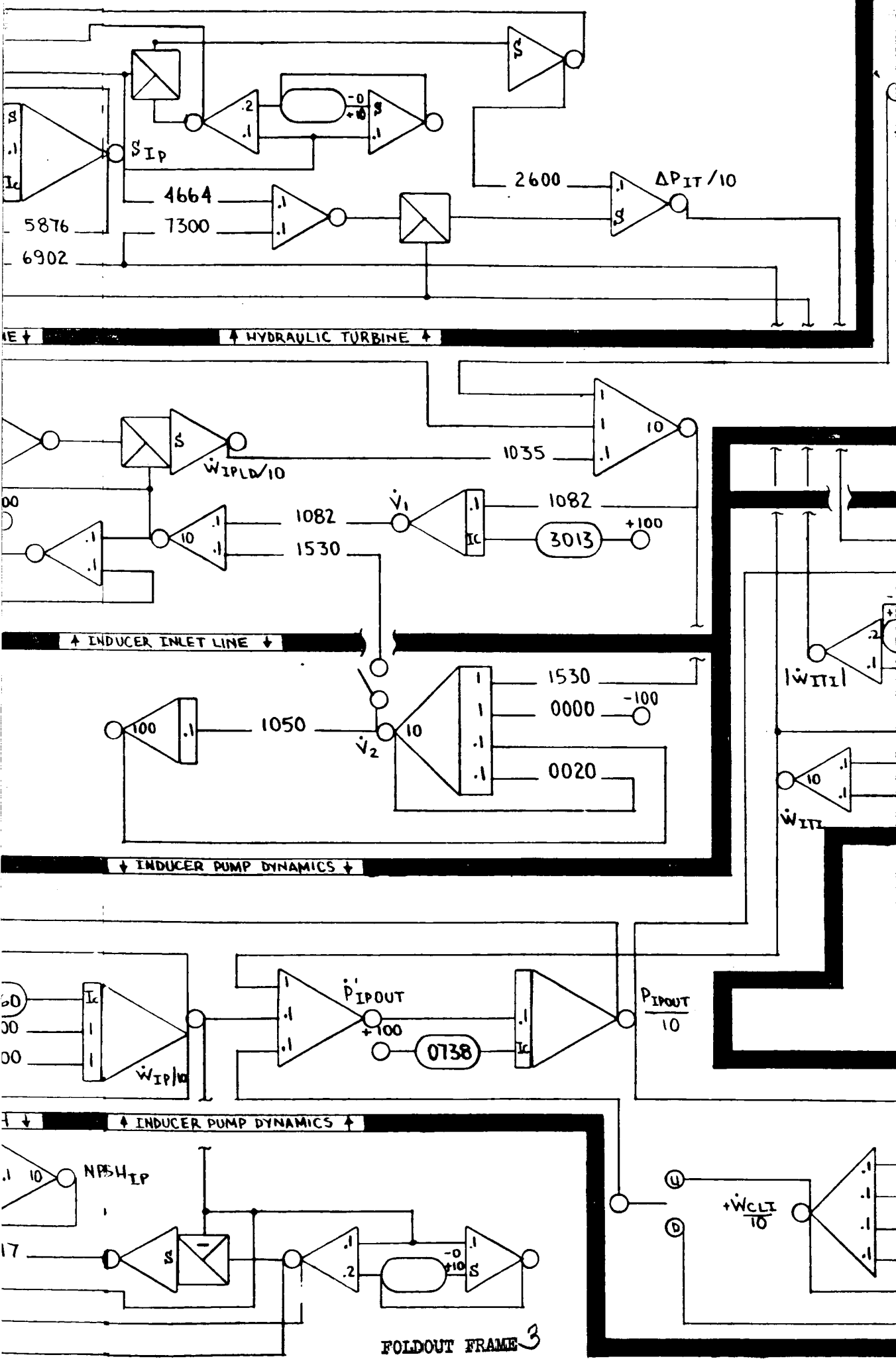
TERCONNECT



FOLDOUT FRAME

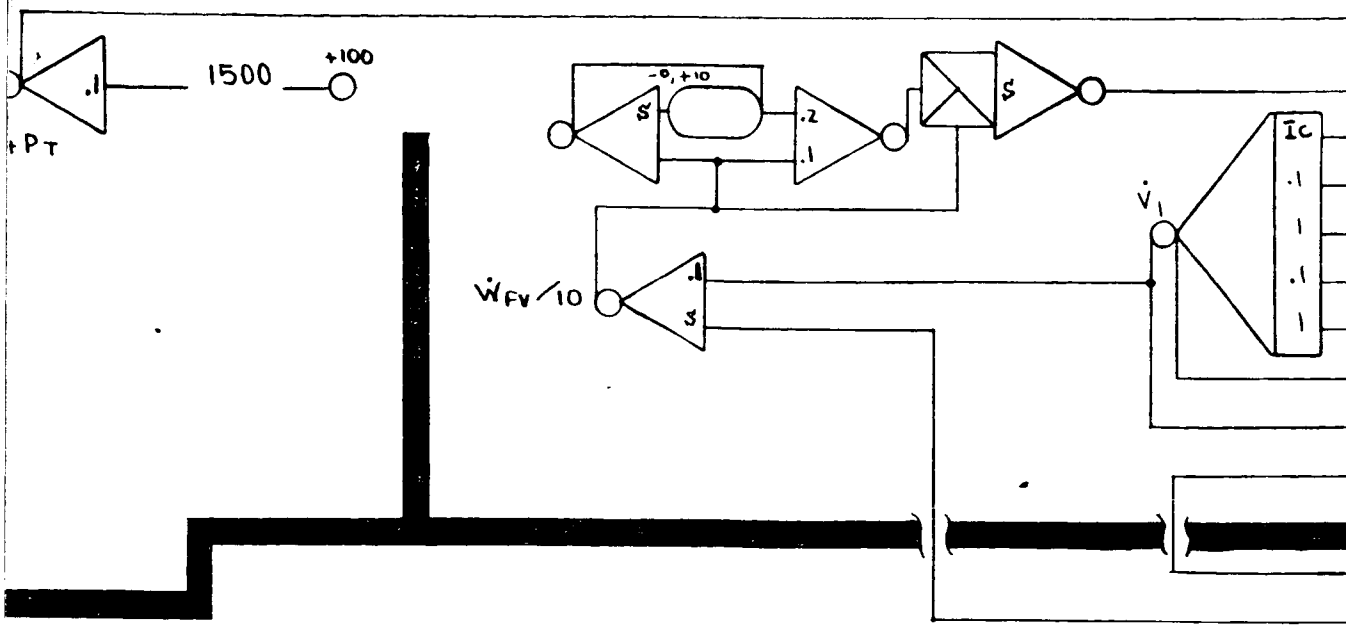
INDUCER


TORQ IP/100
4160
4120
+100
TORQ IT/100
1324
7949
0100
100 $\bar{I}_{DP}/\bar{I}_{DP}$
INDUCER INLET LIN
$P_{IP IN}$
0400
9325
$\bar{I}_{DP}/10$
$\dot{W}_{IP}$
+100
32
25
00
INDUCER PUMP NPS
2308
$\Delta NPSH_{IP}$
00
5303
$10\,\alpha_I$
FOLDOUT FRAME 2

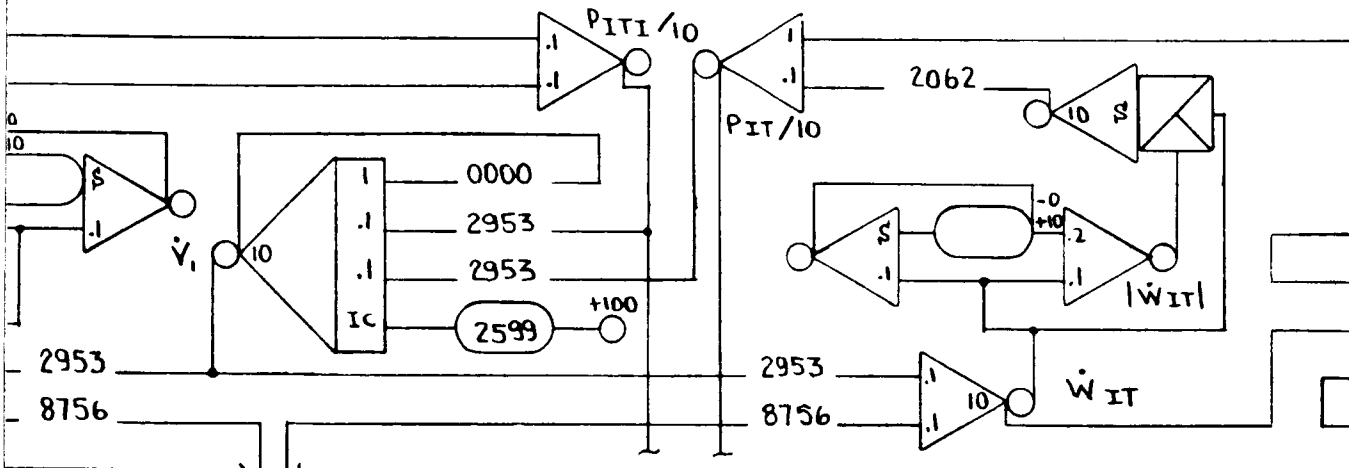

HYDRAULIC TURBINE
INDUCER INLET LINE
INDUCER PUMP DYNAMICS
INDUCER PUMP DYNAMICS
4664
7300
5876
6902
2600
1035
1082
1530
1050
1530
0000
0020
3013
0738
+100
-100
FOLDOUT FRAME 3

TANK

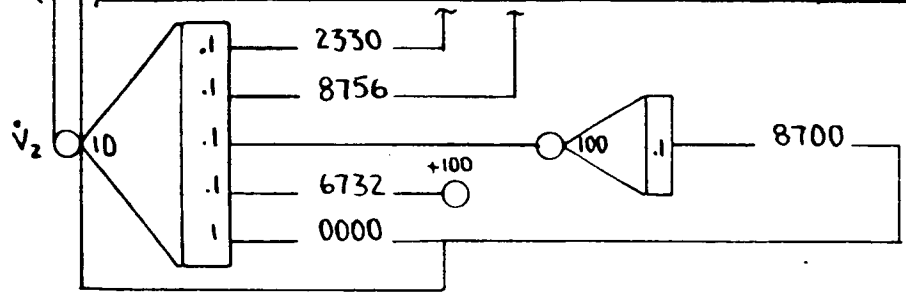
↓ RETURN LINE 1ST MODE ↓



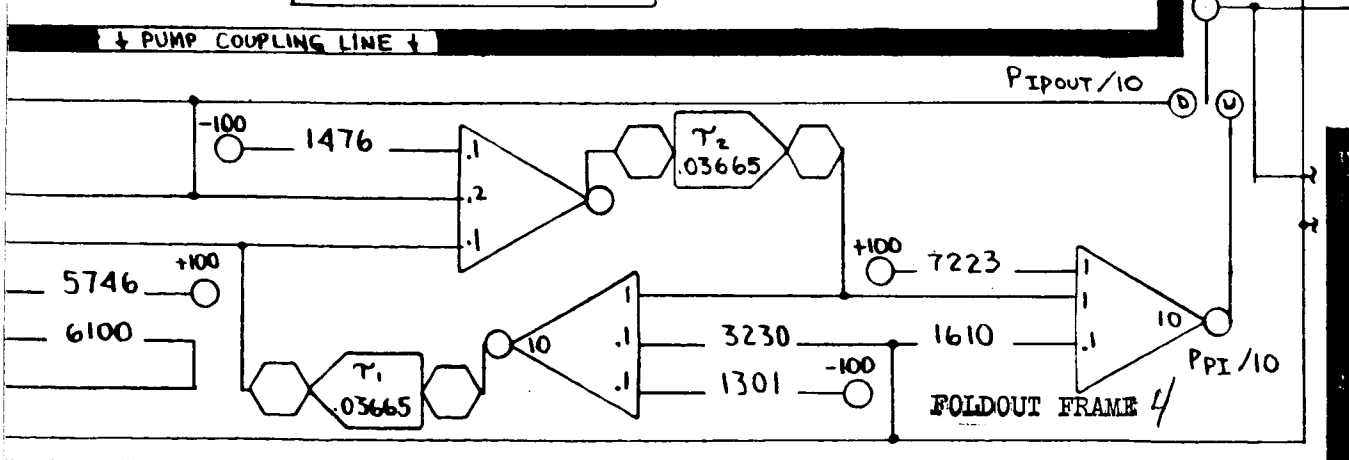
↓ HYDRAULIC TURBINE FEED LINE ↓



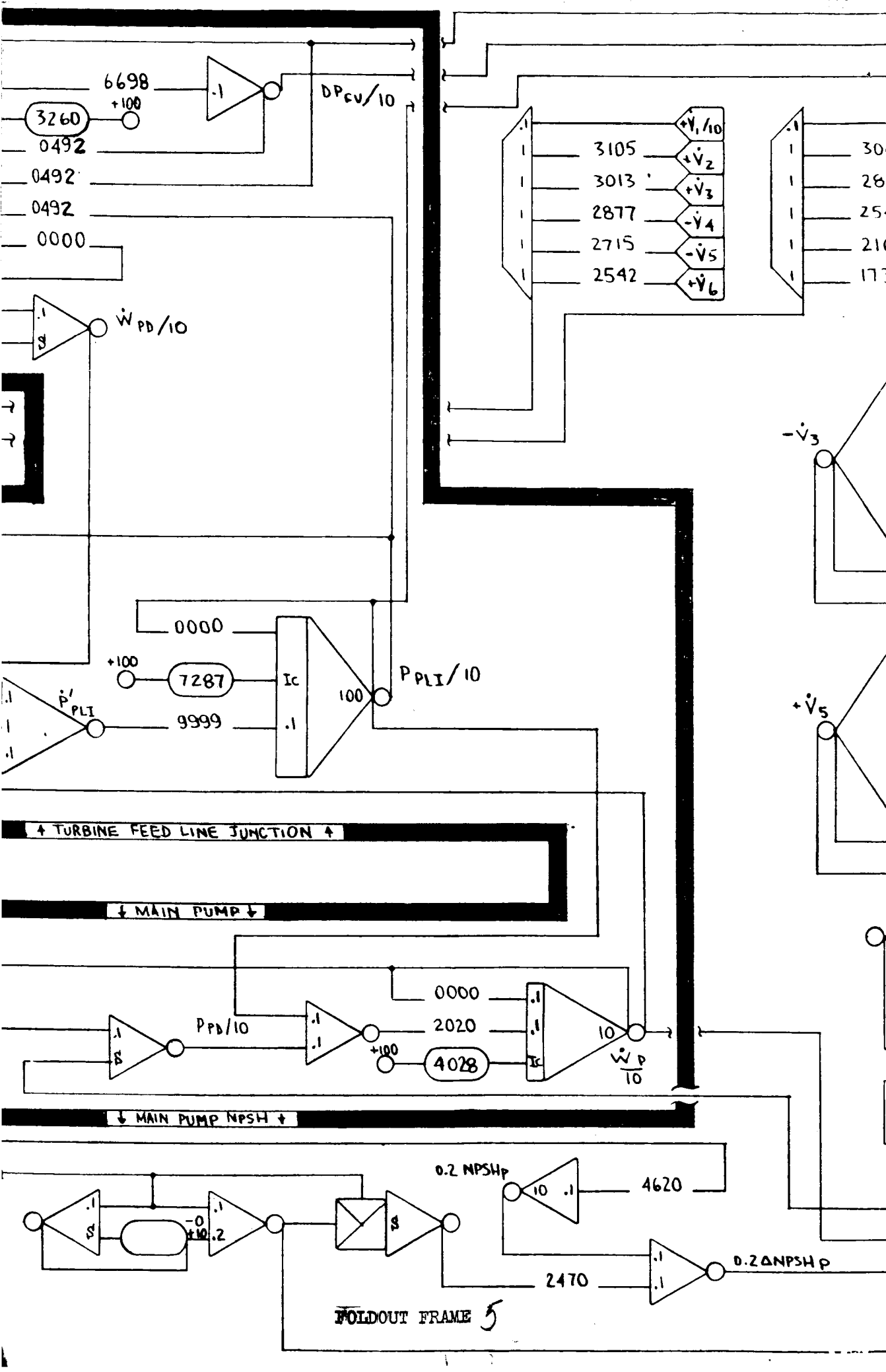
↓ HYDRAULIC TURBINE FEED LINE ↓



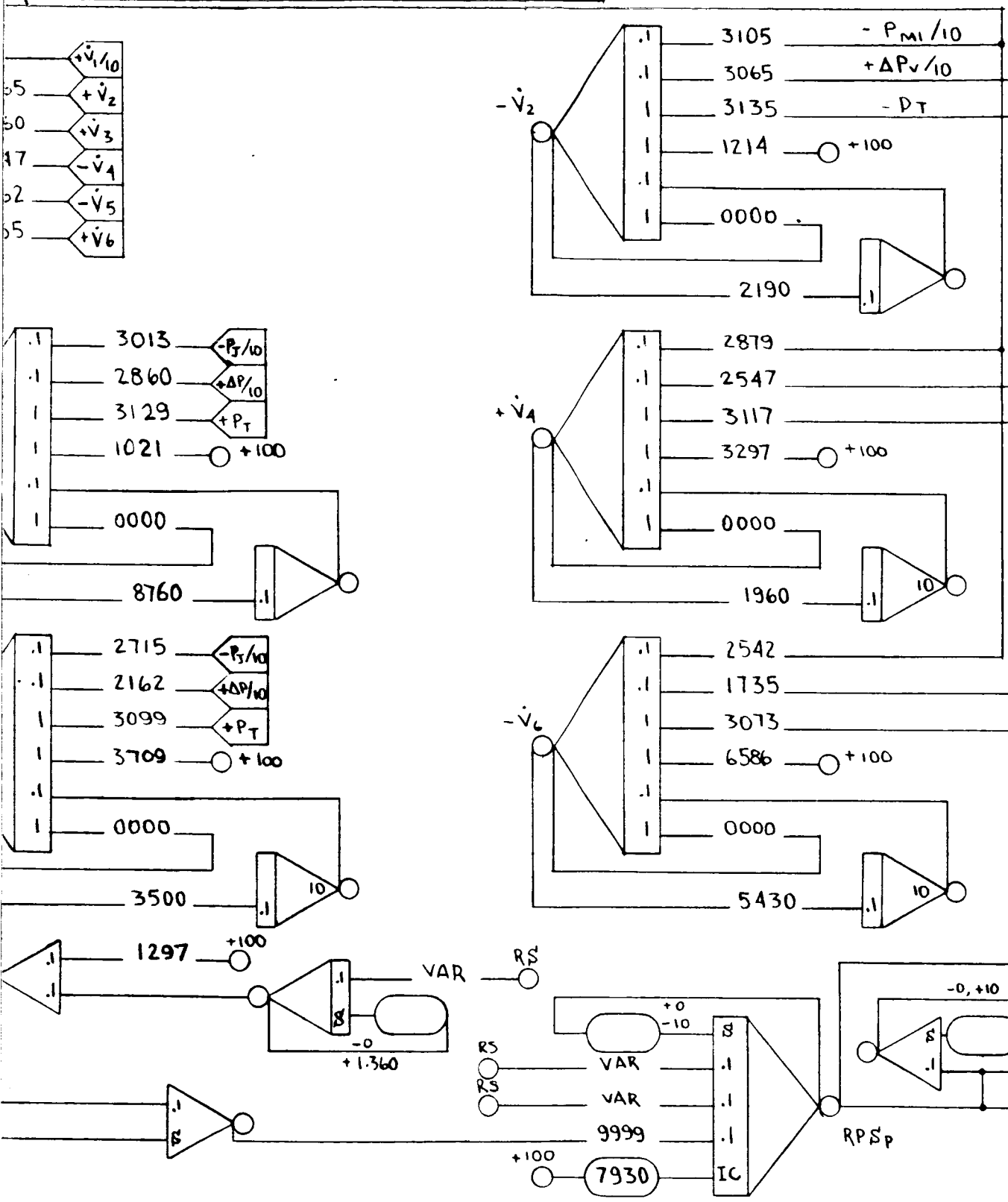
↓ PUMP COUPLING LINE ↓



↑ PUMP COUPLING LINE ↑

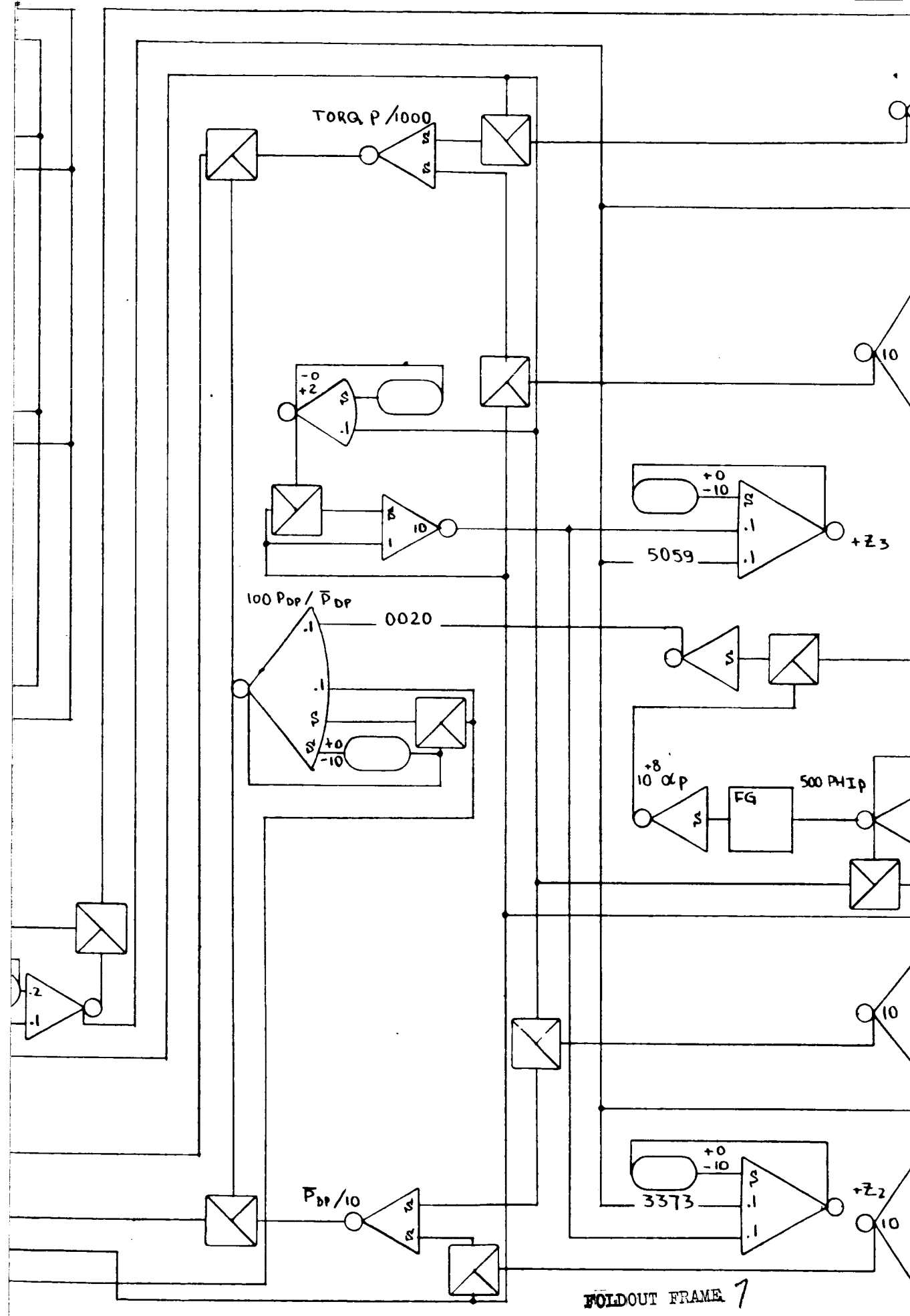

6698
+100
3260
0492
0492
0492
0000
DP_CU/10
3105
3013
2877
2715
2542
+V̇1/10
+V̇2
+V̇3
-V̇4
-V̇5
+V̇6
Ẇ PD/10
-V̇3
0000
+100
7287
Ic
100
P PLI/10
Ṗ'PLI
9999
.1
+V̇5
TURBINE FEED LINE JUNCTION
MAIN PUMP
0000
2020
+100
4028
Ic
10
Ẇ P/10
P PD/10
MAIN PUMP NPSH
0.2 NPSHp
10
4620
0.2ΔNPSH p
2470
FOLDOUT FRAME 5

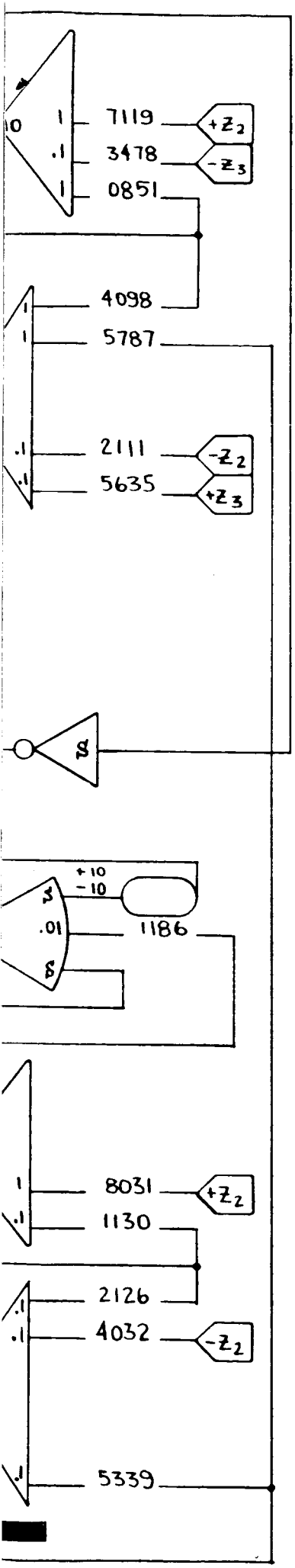
RETURN LINE HIGHER FREQUENCY MODES



MAIN PUMP DRIVE

FOLDOUT FRAME 6


TORQ P /1000
-0
+2
.1
10
+0
-10
.1
.1
+Z3
5059
100 PDP / P̄DP
0020
.1
.1
+0
-10
+8
10 αp
FG
500 PHIP
.2
.1
10
P̄DP /10
+0
-10
3373
.1
.1
+Z2
10
FOLDOUT FRAME 7



Preinducer Analog Model Diagram

FOLDOUT FRAME 8

SAMPLE PLOTTED OUTPUT

PRE-INDUCER-PUMP TEST SYSTEM-REMOTE COUPLING PAGE 1

PIPIN VERSUS TIME

MINIMUM 0.0 MAXIMUM 2.5000E 01

TIME	PIPIN	I
0.0	1.5000E 01	----------+
8.0000E-02	1.4995E 01	----------+
1.6000E-01	1.4883E 01	----------+
2.4000E-01	1.4489E 01	---------+
3.2000E-01	1.3826E 01	--------+
4.0000E-01	1.3170E 01	-------+
4.8000E-01	1.2628E 01	-------+
5.6000E-01	1.1993E 01	------+
6.4000E-01	1.0928E 01	-----+
7.2000E-01	1.1481E 01	-----+
8.0000E-01	1.0506E 01	-----+
8.8000E-01	1.1466E 01	-----+
9.6000E-01	1.1417E 01	-----+
1.0400E 00	1.1192E 01	-----+
1.1200E 00	1.0583E 01	-----+
1.2000E 00	1.0082E 01	----+
1.2800E 00	1.0042E 01	----+
1.3600E 00	9.7575E 00	----+
1.4400E 00	9.4584E 00	---+
1.5200E 00	9.1624E 00	---+
1.6000E 00	8.8486E 00	---+
1.6800E 00	8.5690E 00	---+
1.7600E 00	8.3016E 00	---+
1.8400E 00	8.0104E 00	---+
1.9200E 00	7.7281E 00	---+
2.0000E 00	7.4331E 00	---+
2.0800E 00	7.1430E 00	---+
2.1600E 00	6.8485E 00	---+
2.2400E 00	6.5564E 00	---+
2.3200E 00	6.2600E 00	---+
2.4000E 00	5.9676E 00	---+
2.4800E 00	5.6732E 00	---+
2.5600E 00	5.3830E 00	---+
2.6400E 00	5.0912E 00	---+
2.7200E 00	4.8001E 00	---+

PREINDUCER ANALOG MODEL DIAGRAM

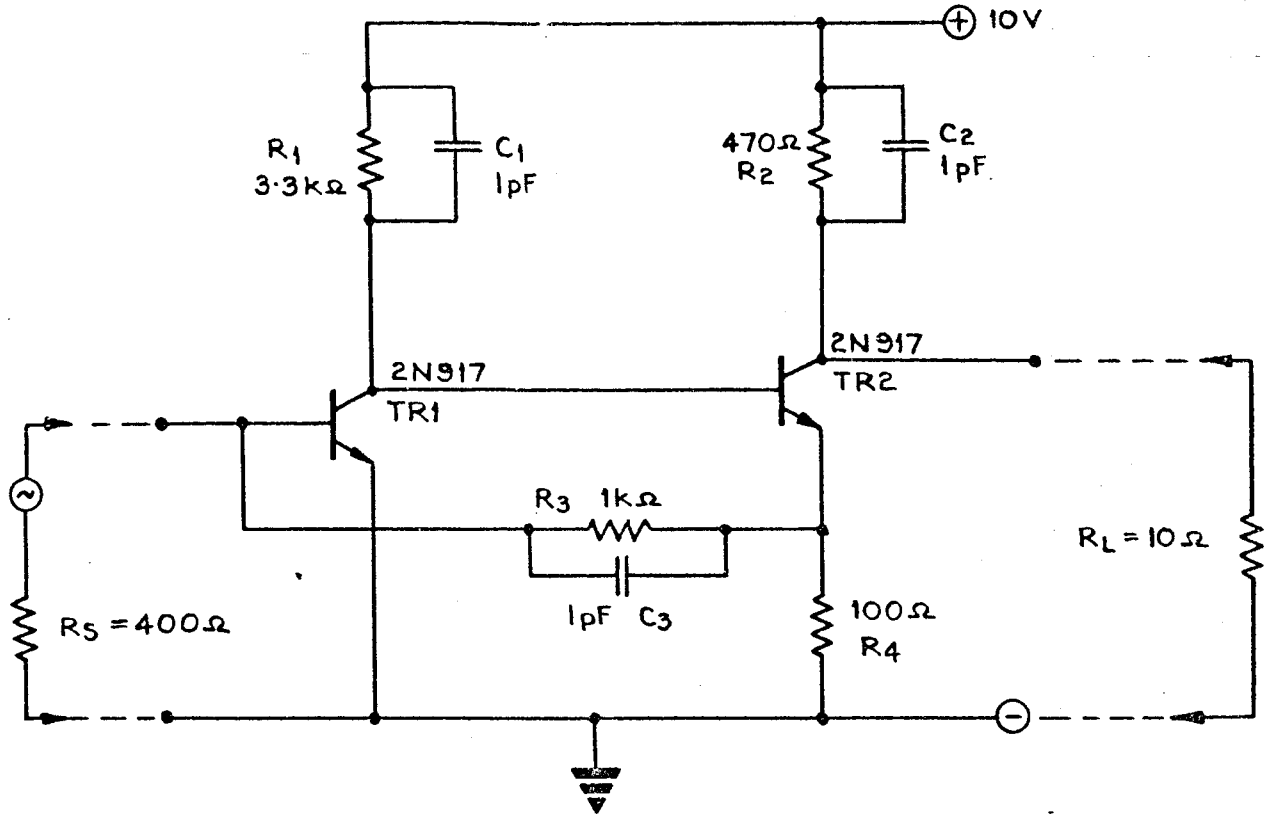


FIG.4a TYPICAL CIRCUIT TO BE ANALYSED

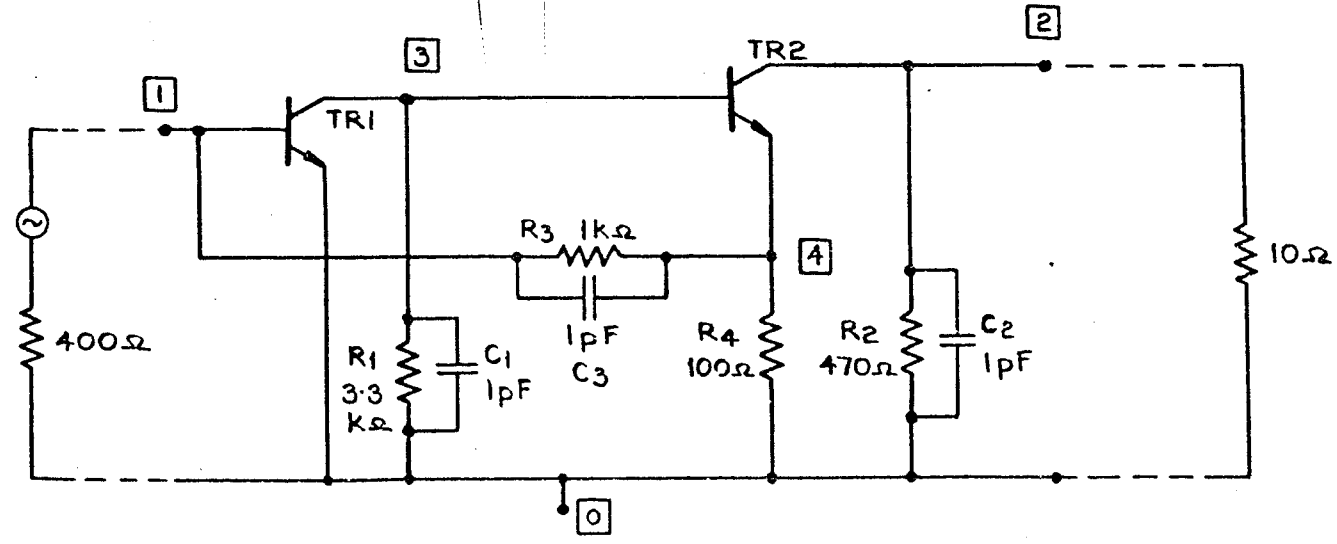


FIG.4b CIRCUIT RE-DRAWN FOR COMPUTER ANALYSIS

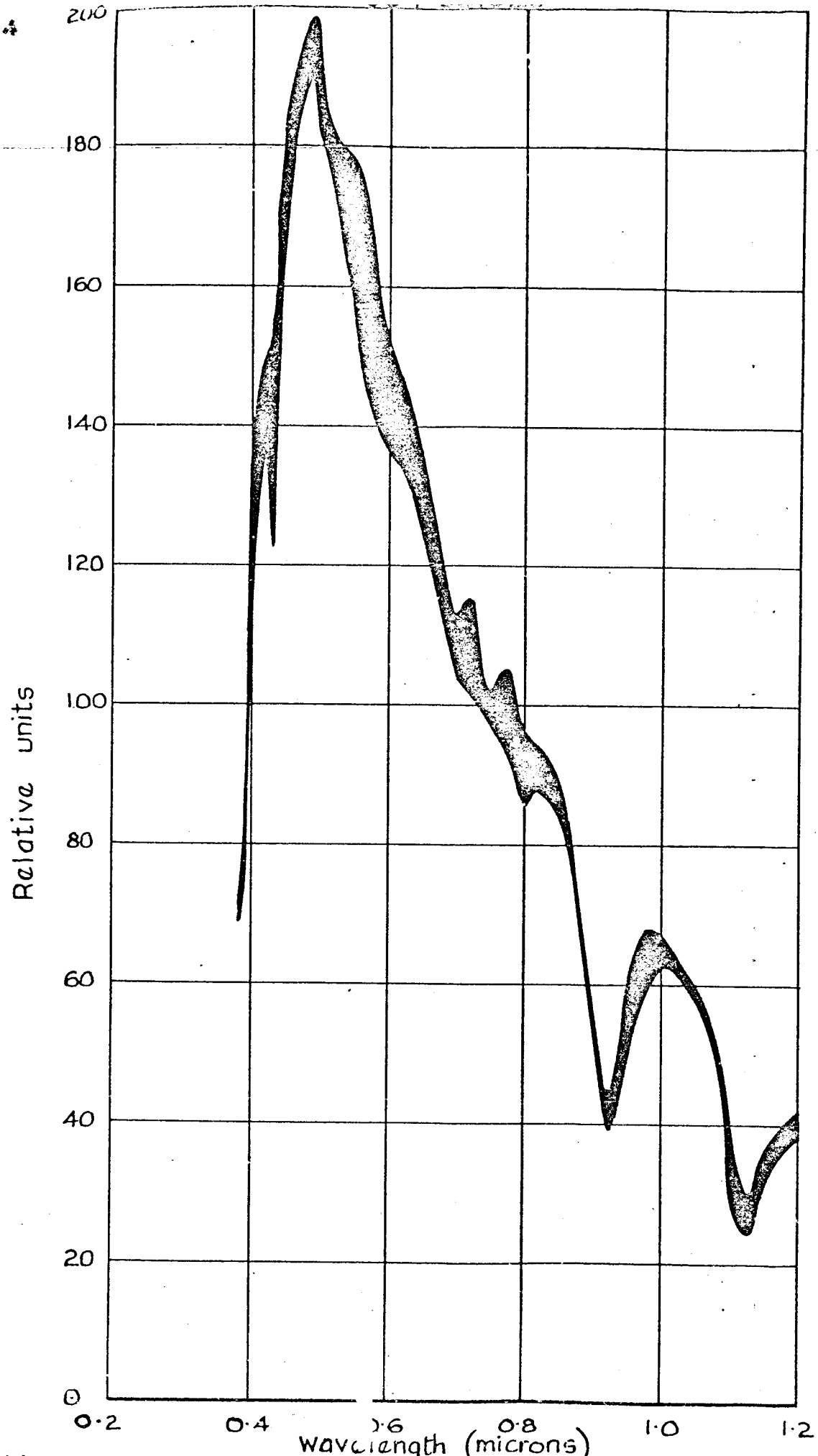


Fig.14 Variation of relative spectral energy distribution noon, 2, 3 & 4 July 1966

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13. ABSTRACT

Two computer programs, an analog and a digital, have been developed that will predict the transient performance of a low-speed inducer driven by a hydraulic turbine. An inducer-turbine unit has been designed and fabrication is in progress. Steady-state maps of the pertinent components of this unit have been constructed from existing test data and by synthetic mapping procedures. These maps have been used in the computer programs to predict the performance of this unit in the system in which it will eventually be tested. Parametric studies have been made to determine the effect of selected changes in this system. The computer program has also been used to investigate several inducer-turbine combinations in simulated rocket engine installations.

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Inducer dynamics						
Hydraulic turbine drive						
Preinducer						
Inducer						